Scientific Problems of the Humid Tropical Zone Deltas and their Implications

Proceedings of the Dacca Symposium

Les problèmes scientifiques des deltas de la zone tropicale humide et leurs implications

Actes du colloque de Dacca

Jointly organized by
the Government of Pakistan and Unesco
24 February to 2 March 1964

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U N E S C O

Humid Tropics Research

Recherches sur la zone tropicale humide

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Foreword

In many respects the delta areas are the most important regions of the humid tropics since they are those of greater human concentration. The scientific problems of the deltas result from their geographical, geological, hydrological, pedological and biological characteristics and from the delicate interrelations between these, with the result that their study greatly benefits from an integrated approach. This was recognized by the Advisory Committee for Humid Tropics Research as early as August 1961 when, at its third session, it recommended that a symposium be held on the subject of deltas as part of the 1963-64 programme.

Consequently a symposium was organized and held in Dacca (East Pakistan) from 24 February to 2 March 1964. A more suitable location could hardly have been selected since the Brahmaputra-Ganges delta—one of the most densely populated regions of the world—is one in which serious problems arise as a result of the rapidly increasing needs of developing towns, industries and roads for an ever-growing population. On this occasion a very interesting field excursion by boat was organized by the Pakistan authorities before the opening of the symposium.

The symposium was sponsored by Unesco, the Pakistan Academy of Sciences, the Pakistan Council of Scientific and Industrial Research, the Pakistan Association for the Advancement of Science, and the University of Dacca which also acted as host. More than fifty specialists from various countries and various fields of science were invited to participate in an exchange of views with a number of Pakistani experts and to discuss the scientific problems of the deltaic regions. The papers presented at this meeting and a summary of the discussion which followed are grouped in the present volume of the "Humid Tropics Research" series under the seven sections which formed the programme of the symposium, i.e.:

I. Geomorphology, sedimentation and pedology;
II. Hydrography and hydrology;
III. Vegetation;
IV. Biology;
V. Human influence;
VI. Descriptive studies;
VII. Classification of deltas.

In presenting this volume to its readers Unesco wishes to thank Dr. M. S. Sharif, Secretary to the Ministry of Education of the Pakistan Government, who played a major role in the preparations for the symposium and delivered the inaugural speech. Warm thanks are also due to Dr. M. O. Ghani, Vice-Chancellor of the Dacca University, Dr. Raziuddin Siddiqui, President of the Pakistan Academy of Sciences and Dr. Salimuzzaman Siddiqui, President of the Pakistan Council of Scientific and Industrial Research, who were responsible for organizing the symposium and for the local arrangements, including the field excursion, and who ensured the scientific success of this international meeting.

Avant-propos

A BIEN des égards, les deltas sont les régions les plus importantes de la zone tropicale humide, car ce sont celles où la concentration humaine est la plus forte. Les problèmes scientifiques concernant les deltas procèdent de leurs caractéristiques géographiques, géologiques, hydrologiques, pédologiques et biologiques et des rapports délicats qui existent entre elles, de sorte qu'il y a grand avantage à les étudier dans leur ensemble. C'est ce que le Comité consultatif international de recherches sur la zone tropicale humide a reconnu dès le mois d'août 1961, à sa troisième session, quand il a recommandé qu'un colloque soit organisé, dans le cadre du programme de 1963-1964, sur ces problèmes des deltas.

Dès lors, le colloque s'est tenu à Dacca, dans le Pakistan-Oriental, du 24 février au 2 mars 1964. Le choix du lieu était particulièrement heureux, puisque le delta formé par le Brahmapoutre et le Gange — qui est l'une des régions du monde où la densité de la population est le plus élevée — est aussi l'une de celles où se posent des problèmes particulièrement graves, inhérents à la nécessité de plus en plus impérieuse de développer villes, industries et routes pour répondre aux besoins d'une population sans cesse croissante.

Avant l'ouverture du colloque, les autorités pakistanaises avaient d'ailleurs organisé, à l'intention des participants, une excursion en bateau dans la région, qui a été du plus vif intérêt.

Le colloque était organisé sous l'égide de l'Unesco, de l'Académie des sciences du Pakistan, du Conseil pakistanais de la recherche scientifique et industrielle, de l'Association pakistanaise pour l'avancement des sciences et de l'Université de Dacca, qui accueillit les participants. Plus de cinquante spécialistes venus de divers pays et représentant diverses disciplines scientifiques avaient été invités à participer à des échanges de vues avec un certain nombre d'experts pakistanais et à examiner les problèmes scientifiques des régions deltaïques.

On trouvera dans le présent volume de la collection "Recherches sur la zone tropicale humide" les exposés présentés à ce colloque, ainsi que le résumé des discussions auxquelles ils ont donné lieu. Ils sont groupés sous les sept rubriques qui constituaient le programme du colloque :

I. Géomorphologie, sédimentation et pédologie;
II. Hydrographie et hydrologie;
III. Végétation;
IV. Biologie;
V. Influences de l'homme;
VI. Études descriptives;
VII. Classification des deltas.

En présentant les travaux de ce colloque à ses lecteurs, l'Unesco se doit de remercier M. M. S. Sharif, secrétaire à l'éducation du gouvernement pakistanais, qui a joué un rôle de premier plan dans la préparation du colloque et qui a prononcé l'allocution d'ouverture. De chaleureux remerciements sont dus également à MM. M. O. Ghani, recteur de l'Université de Dacca, Raziuddin Siddiqui, président de l'Académie des sciences du Pakistan et Salimuzzaman Siddiqui, président du Conseil de la recherche scientifique et industrielle du Pakistan, qui ont bien voulu organiser le colloque et les activités connexes, y compris l'excursion dans le delta, et qui ont assuré, sur le plan scientifique, le succès de cette rencontre internationale.

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I

Geomorphology, sedimentation, pedology
Géomorphologie, sédimentation et pédologie

La place de la géomorphologie dans l'étude de la mise en valeur des deltas tropicaux

J. Tricart

Certains progrès scientifiques récents peuvent contribuer à rendre plus facile la solution du difficile problème de la mise en valeur des deltas tropicaux. Tel est le cas de certaines conceptions modernes de la géomorphologie, susceptibles d'application. Depuis dix ans, nous avons eu l'occasion d'en faire la preuve, principalement dans le delta du Sénégal et dans le delta intérieur du Niger et, en même temps, de forger un instrument plus apte à satisfaire aux exigences des techniciens et des spécialistes des autres disciplines.

QUELQUES ASPECTS GÉOMORPHOLOGIQUES DES DELTAS TROPICAUX

A l'heure actuelle, malgré des progrès récents, l'unité de vue est encore loin d'être faite sur les conceptions fondamentales de la géomorphologie et sur son orientation. Pour certains, la géomorphologie reste avant tout une discipline descriptive qui se contente d'identifier simplement les formes du terrain et de permettre leur classement dans des catégories élaborées il y a plus d'un demi-siècle par W. M. Davis. Souvent, surtout aux États-Unis, on donne le nom de *physiographie* à cette branche des sciences de la terre qui n'est qu'une annexe, sans grande originalité, de la géologie.

Mais, essentiellement en Europe, en Allemagne d'abord puis maintenant surtout en France et en Pologne, une autre conception de la géomorphologie s'est développée. C'est elle qui est susceptible d'applications, car elle permet une connaissance beaucoup plus profonde et plus nuancée de certains aspects du milieu physique qui intéressent les aménagements destinés à améliorer l'utilisation des ressources naturelles.

Pour nous, la géomorphologie, dont l'objet spécifique est l'étude de l'évolution du modelé de la surface terrestre (Tricart, 1962), analyse se qui se passe le long d'une surface de contact, celle entre la lithosphère et l'atmosphère. Conformément à une loi physique très générale, cette surface de contact enregistre un équilibre entre les forces qui s'exercent de part et d'autre. La géomorphologie moderne doit donc reposer sur une conception dynamique (géomorphologie dynamique). Elle doit s'attacher à analyser des équilibres et à comprendre comment ils se modifient.

Aussi rappellerons-nous d'abord quelques aspects géomorphologiques des deltas tropicaux, puis la nature des recherches que la géomorphologie pratique. Nous verrons ensuite quelle est leur utilité et comment notre discipline peut s'intégrer le plus harmonieusement et le plus efficacement dans un programme général de recherches. Dans le cas des deltas, un équilibre géomorphologique résulte de l'interférence entre :

a) Les forces internes, qui se caractérisent très souvent par un mouvement de subsidence;

b) Les actions de la mer, qui attaquent la face externe du delta et en reprennent le matériel pour le transporter plus loin sous la forme de la dérive littorale. Or les variations de niveau glacio-eustatiques rendent cette action marine particulièrement changeante;

c) Les apports fluviaux, provenant du bassin du fleuve, et qui sont commandés par l'intensité de l'érosion, la nature et l'abondance du transport des débris. Or ces apports varient avec tout ce qui influe sur la dynamique du fleuve et sur l'érosion dans le bassin versant.

L'équilibre d'un delta est ainsi particulièrement complexe. Les variations du niveau marin qui peuvent y apparaître sont le résultat d'une somme algébrique entre les oscillations glacio-eustatiques générales, de mieux en mieux connues pour l'ensemble du globe, et les effets locaux de la subsidence, elle-même variable dans le temps et dans l'espace et influencée, en partie, par le poids des sédiments qui s'accumulent. Par exemple, dans le delta du Sénégal, le niveau marin dunkerquien (maximum de la transgression flandrienne, environ 4 000 BP) ne présente pas de déformations appréciables. Par contre, le niveau ouljien (dernier interglaciaire) est un peu déprimé et se rencontre vers 4-5 mètres au lieu de 6-8 mètres. Enfin, aucun niveau du quaternaire ancien n'a été rencontré. Toutes les formations de cet

âge observées sont terrestres, ce qui implique qu'à cette époque le littoral se trouvait plus au large et que la faible altitude de ces formations est due à une subsidence postérieure à leur dépôt. La principale période d'affaissement serait donc préouljienne, ce qui rendrait d'ailleurs compte de l'extension et de l'épaisseur des dépôts de cette période.

Quant aux apports terrestres, ils dépendent en grande partie du climat. Ce sont les oscillations climatiques qui rythment leur arrivée et qui commandent leurs faciès. Dans une grande partie de la zone tropicale humide d'Afrique occidentale, nous avons pu établir l'existence de périodes plus sèches que l'actuelle, pendant lesquelles la forêt se réfugiait aux alentours du mont Cameroun et au Libéria. Les savanes arrivaient au bord du golfe de Guinée en Côte-d'Ivoire. Leur existence semble d'ailleurs liée plus à une irrégularité des précipitations qu'à une diminution massive de leur hauteur moyenne totale annuelle. Ces périodes ont été caractérisées par des climats particulièrement agressifs, avec mise en marche de masses considérables de débris sur les versants, décapés par les ruissellements diffus, ennoyage des vallées sous des nappes de cailloutis et de sables parcourues par des rivières à chenaux anastomosés (« graviers sous berge » des prospecteurs miniers sur lesquels J. Vogt a justement attiré l'attention). Des masses considérables de débris sont alors arrivées jusqu'à la mer. En Côte-d'Ivoire, ce régime s'est reproduit à trois reprises au cours du quaternaire, depuis la mise en place du continental terminal. Lors des deux dernières, les apports grossiers se sont continués, tout en diminuant, lors de la transgression (ouljienne d'une part, flandrienne de l'autre). Des deltas se sont alors construits dans les rias où débouchaient les fleuves, mais la subsidence, parfois très rapide, de la zone lagunaire, a provoqué leur submersion. Une partie des matériaux sableux apportés a été cependant redistribuée par la mer le long de la côte, formant le cordon littoral qui ferme les lagunes. Au dunkerquien, en arrière de lui, dans les eaux plus calmes, des deltas importants se sont construits, partiellement recouverts par les crues actuelles, qui apportent davantage de sédiments fins. On a donc ainsi une superposition de produits de décantation argileux à d'anciennes levées sableuses dunkerquiennes là où celles-ci n'étaient pas trop hautes. Ailleurs, les levées sableuses dunkerquiennes forment des unités insubmersibles, recoupées par des levées sableuses actuelles submersibles.

Sur le littoral du Brésil oriental, le dunkerquien a été marqué par une courte crise climatique, avec un climat à pluies plus irrégulières ayant accru la torrentialité des cours d'eau et, par conséquent, les apports sableux. Dans beaucoup de deltas, on rencontre des faisceaux très développés de levées sableuses souvent insubmersibles, qui se raccordent à des cordons littoraux. Les crues actuelles inondent les espaces déprimés entre les cordons, transformés en marais à sédimentation organique lorsque les apports fins pénètrent mal, en cuvettes de décantation argileuse dans le cas contraire. Le littoral actuel recoupe souvent les systèmes de cordons et de levées dunkerquiennes et la dérive littorale reprend leur matériel, attaqué en microfalaises, l'abandonnant plus loin, où il isole des lagunes ou engraisse des côtes basses. Dans l'ensemble la diminution postdunkerquienne des apports terrestres se traduit par une régularisation de la côte, avec recoupement des anciens deltas plus proéminents.

Dans le delta du Sénégal, sur la marge de la zone désertique, l'évolution fut encore plus contrastée. Le fleuve s'est pratiquement perdu dans les sables sans atteindre le delta lors des deux dernières périodes sèches, surtout lors de l'avant-dernière, coïncidant avec des régressions marines. Des champs de dunes se sont alors formés sur les alluvions du delta. Lors de la transgression ouljienne, puis de la transgression dunkerquienne, la mer a pénétré entre ces dunes, formant un golfe digité alors que le fleuve redevenait plus abondant. Progressivement les apports terrestres accrus ont envahi et partiellement colmaté le golfe, converti d'ailleurs simultanément en lagune par la progression d'un cordon littoral. On retrouve ainsi les traces de deux deltas lagunaires successifs, l'un ouljien, l'autre dunkerquien, qui ont colmaté plus ou moins complètement les lagunes issues du golfe formé lors de la transgression. Or les levées alluviales dunkerquiennes, mises en place dans une lagune sursalée, se sont incorporé beaucoup de sel qui remonte par capillarité lorsque le matériel est sablo-limoneux, ce qui a une importance pratique considérable.

Ces quelques exemples, choisis exclusivement dans des deltas de la zone intertropicale, montrent comment la géomorphologie moderne vise à une interprétation aussi dynamique que possible des unités du modelé et tente de préciser l'âge et les conditions de leur mise en place. Elle y arrive grâce à un recours constant à des méthodes qui se sont développées au cours des dernières années et qui lui ont permis, justement, de se rénover.

NATURE DES RECHERCHES GÉOMORPHOLOGIQUES

Les étapes de l'analyse géomorphologique sont les suivantes :

1. L'*identification des formes*, qui est essentiellement de nature dynamique. Le vocabulaire géomorphologique, pour cette raison, diffère du vocabulaire topographique, uniquement géométrique et descriptif. Ce n'est que lorsqu'il est en présence de formes d'une part suffisamment caractéristiques, d'autre part d'origine problématique, que le vocabulaire géomorphologique se contente de termes descriptifs. Dans le cas des deltas, c'est par l'intermédiaire des agents qui les ont édifiés que nous distinguons les cordons littoraux, construits par les processus littoraux, et les levées alluviales, accumulées par le courant des fleuves en crue. De même,

des termes qui reviennent souvent, comme « cuvette de décantation », « delta de rupture de levée », « marigot de vidange, » etc., ont étymologiquement un contenu génétique. Cette identification des formes se fait sur le terrain, avec l'aide des photographies aériennes, par l'observation de certains critères caractéristiques. Il est parfois nécessaire de la compléter par l'examen d'échantillons en laboratoire, surtout quand il s'agit de formes anciennes, qui ne sont plus fonctionnelles et dont, pour cette raison, certains aspects sont oblitérés.

L'étude de laboratoire, telle qu'elle est conduite par le géomorphologue, emprunte une grande partie de ses méthodes à la sédimentologie, parfois à la pédologie. Mais elle est réalisée avec une finalité particulière : identifier les processus qui permettent de définir la genèse de la forme considérée. Par exemple, un cordon littoral et une levée alluviale, dont les caractéristiques topographiques peuvent être analogues, se différencient par la granulométrie du matériel, généralement mieux triée dans le cas du cordon, par le façonnement des grains de sable quartzeux à certaines dimensions, par la composition pétrographique du matériel.

2. La *datation des formes*, une fois effectuée leur identification. Cette opération est parfois plus incertaine et, dans la plupart des cas, le géomorphologue se contente de datations relatives. Il établit alors une succession des formes. Celle-ci est évidente sur le terrain, dans certains cas. Par exemple, des bras de fleuve, accompagnés de levées, qui recoupent des cordons littoraux sont forcément plus récents qu'elles. Mais il n'en est pas toujours ainsi. Il faut alors recourir à des méthodes indirectes.

Le degré d'altération superficielle du matériau en est une. Il est particulièrement utilisable dans le cas des deltas intertropicaux, où cette altération est généralement intense et rapide. Par exemple, en Côte-d'Ivoire comme à Bahia (Brésil), les cordons littoraux ouljiens sont toujours exclusivement formés de sable quartzeux parfaitement lessivé. Les débris calcaires et les oxydes de fer, les micas, les feldspaths, ont complètement disparu sur 1 mètre d'épaisseur et plus, ce qui n'est pas le cas des cordons dunkerquiens.

Les particularités pétrographiques du matériel peuvent servir également. Par suite des modifications des conditions morphogénétiques liées au climat ou à des changements de configuration des bassins, les apports successifs d'un même fleuve n'ont pas exactement la même composition pétrographique. Une fois solidement établi à partir d'accumulations datées par d'autres méthodes, le critère peut être utilisé dans les cas douteux.

Ces travaux de laboratoire complètent ceux qui sont destinés à identifier les formes. Ils peuvent aboutir à préciser certaines nuances génétiques qui sont en rapport avec des changements paléogéographiques. Par exemple, dans le delta du Sénégal, les levées alluviales dunkerquiennes sont toujours formées de sable un peu plus grossier que les levées actuelles, ce qui implique des crues un peu plus fortes, avec un courant plus violent. Effectivement, elles sont souvent, également, plus hautes.

Ces identifications paléogéographiques sont très précieuses pour l'établissement des chronologies relatives et leur rattachement aux faits plus généraux qui donnent une datation mondiale. Par exemple, notre chronologie du delta du Sénégal fut établie en combinant les changements de dynamique successifs provoqués par le climat et les oscillations du niveau marin. C'est à partir de celles-ci que nous pouvons parler de dunes pré-ouljiennes ou de levées dunkerquiennes. Mais les caractéristiques du matériel issues de ces oscillations paléoclimatiques ayant été retrouvées dans le delta intérieur du Niger, nous avons pu les utiliser pour proposer une échelle chronologique des diverses formations de cette région, bien qu'aucun raccord avec les niveaux marins quaternaires, fil conducteur, ne soit possible.

De toute manière, même quand les équivalences avec une chronologie plus générale restent douteuses ou hypothétiques, ces méthodes fournissent le moyen d'établir une succession génétique, ce qui est le plus important, surtout pour les exigences pratiques.

3. La *cartographie des formes*, étape décisive des recherches détaillées, bien que peu de géomorphologues la pratiquent systématiquement. Le système que nous avons mis au point depuis 1953, en tenant compte des autres expériences, notamment de celle des Polonais, aboutit à prendre en considération les éléments suivants :

a) Certains caractères morphométriques des formes, destinés à compléter la carte topographique ou à pallier son absence. Tel est le cas, par exemple, de la hauteur des berges sapées le long des cours d'eau, des dénivellations des levées alluviales et des cordons littoraux, etc. La disposition des crêtes de ces formes, le dessin des deltas de rupture de levées, des cuvettes de décantation est également souligné au moyen de l'adoption de signes appropriés. Des indications de microtopographie fort utiles sont ainsi fournies.

b) La nature dynamique des formes, identifiée suivant les conceptions exposées plus haut.

c) Leur âge, déterminé comme nous venons de l'exposer. Lorsqu'une étiquette stratigraphique peut être donnée, nous le faisons. Sinon, nous distinguons des terrasses successives, dans leur ordre d'ancienneté, au moyen de symboles : t_1, t_2, t_3, t_4 etc.; éventuellement au moyen de subdivisions supplémentaires, des détails peuvent être ajoutés : t_{1a} et t_{1b}, par exemple, sont deux subdivisions successives de t_1. Le même type de notations peut être appliqué au plages marines, aux cordons littoraux successifs, aux levées alluviales, aux dunes, etc.

d) La nature du matériel. Dans le cas des constructions détritiques que sont les deltas, c'est essentiellement

la granulométrie qui est prise en considération. Le système adopté permet de représenter non seulement les matériaux purs, graviers, sables, limons et argiles, mais également les mélanges, et de tenir compte, jusqu'à un certain point, des proportions dans lesquelles ils se sont faits. Parfois, nous ajoutons quelques éléments importants, comme les débris organiques ou le sel, les cuirasses ferrugineuses, etc.

Ce système de cartographie fournit ainsi tous les éléments faisant partie de la conception de la géomorphologie la plus complète et la plus exigeante, qui est la nôtre. Une forme est caractérisée dans son extension, dans ses traits topographiques essentiels, par sa genèse, son âge et le matériel qui la constitue. Nous avons réservé les couleurs à la figuration de la chronologie, d'une part parce que leur variété permet de faire face à n'importe quelle complexité, d'autre part pour ne pas choquer des utilisateurs généralement habitués aux cartes géologiques sur lesquelles cette convention est adoptée par décision internationale. Caractère des formes, genèse et nature du matériel sont indiqués au moyen de signes dessinés qui peuvent se combiner entre eux, ce qui permet une souplesse totale.

Des expériences faites dans les conditions les plus variées ont montré que le système de cartes géomorphologiques J. Tricart-CGA peut s'adapter à n'importe quel cas, si complexe et si aberrant puisse-t-il être, et qu'il traduit fidèlement le degré de précision des connaissances, ce qui est non moins essentiel. Il s'applique à des échelles allant du 1/1 000 au 1/200 000 pour les deltas, c'est-à-dire, pratiquement, à toutes les échelles usuelles utilisées dans les études d'aménagement.

SERVICES A ATTENDRE DES RECHERCHES GÉOMORPHOLOGIQUES

La mise en œuvre de ces méthodes peut se faire sous la forme de deux étapes successives :

1. Une *reconnaissance*, dans laquelle on définit les caractères généraux de la région. Avec ou sans une cartographie à petite échelle (1/200 000 par exemple), elle aboutit à subdiviser le delta en grands ensembles ayant chacun leurs traits particuliers, leur dynamique originale. Par exemple, dans le delta du Sénégal, nous avons ainsi distingué :

a) Un haut delta, dunkerquien, mis en place dans le fond de l'ancienne lagune, peu submersible, passablement sableux, au microrelief accentué, assez riche en sel, mais pouvant se dessaler facilement avec l'irrigation (lessivage des levées assez poreuses);
Un cadre dunaire, formé de dunes fixées ourlées d'anciennes plages marines sur les bords du golfe, puis de la lagune dans lesquels se sont construits les deltas successifs. Ces dunes sont impropres à une mise en valeur généralisée. Seules, certaines dépressions intermédiaires peuvent être irriguées et servir de points de fixation des nomades;

c) Une région de sebkhas, ancien bas delta dunkerquien, faiblement colmaté, très argileux, difficilement atteint actuellement par les inondations, très salé, domaine d'une intense déflagration éolienne qui saupoudre de sel le reste du delta. Il a été proposé de le noyer avec l'eau de la mer voisine afin d'arrêter la déflation de limons salés nocifs. Cela est d'autant plus facile qu'une bonne partie des sebkhas est au-dessous du niveau des hautes mers;

d) Un bas delta actuel, fonctionnant en régime estuarien en période d'étiage et submergé par l'eau douce lors de la crue annuelle. Il s'y décante des argiles et s'y édifie de petites flèches sableuses. Un endiguement combiné à l'irrigation permettrait le développement de vastes rizières.

De telles reconnaissances, réalisées dans le cadre d'un travail d'équipe, permettent l'établissement d'avant-projets et de programmes d'études plus détaillés. Un géomorphologue exercé, de haute qualification professionnelle, peut donner des indications précieuses sur les conditions hydrologiques, sur la nature des dépôts, leur ancienneté. Or ces caractéristiques influent considérablement sur la qualité des sols et les aptitudes des terres en vue du drainage ou de l'irrigation. L'agronome et le pédologue de l'équipe sont ainsi placés sur un terrain plus solide où ils peuvent travailler plus sûrement et plus rapidement dans leur spécialité. Les renseignements obtenus sur la nature des terrains peuvent également servir à l'ingénieur qui a une idée des ressources en matériaux et des conditions de construction des ouvrages. Enfin, l'observation de la dynamique des bras et des plages permet d'intervenir dans la discussion préalable des aménagements hydrauliques, notamment d'avoir une idée de la migration des débris sous l'effet de la dérive littorale, de l'importance du colmatage des vasières, de l'origine du matériel qui s'y accumule, etc. On peut ainsi évaluer les traumatismes que pourront créer, dans le milieu naturel, tel ou tel type d'installation et en tenir compte dans le choix des avant-projets.

2. Une *étude détaillée*, avec cartographie systématique à des échelles de l'ordre du 1/10 000 au 1/50 000.

Cette étude détaillée donne une image précise et complète des conditions géomorphologiques du delta. Dans les travaux que nous avons réalisés, elle a servi aux fins suivantes :

a) Études pédologiques. La pédogenèse, surtout dans les deltas, est sous l'étroite dépendance des conditions géomorphologiques. Les sols ne prennent un développement aboutissant à des profils caractéristiques que sur les accumulations suffisamment anciennes qui, depuis leur mise en place, ne sont plus recouvertes de nouveaux dépôts et n'ont pas subi un décapage par l'érosion. Comme nos cartes indiquent l'âge des accumulations et la nature de leur matériel, ainsi que les vicissitudes ultérieures qu'elles ont pu connaître, le pédologue dispose là d'éléments très importants qui ont influencé la pédogenèse. En particulier, ils peuvent lui servir

de fil conducteur pour la connaissance des paléosols. Ce fut notamment le cas dans le delta du Sénégal, où les sols rubéfiés sur les dunes fixées anciennes se sont tous révélés être pré-ouljiens et résulter d'une période de climat plus humide que l'actuel. D'autres paléosols, châtain clair, ont été rencontrés sur les dunes récentes.

En général, le pédologue, après vérification, peut reprendre la plupart des tracés de la carte géomorphologique car ceux-ci correspondent généralement à des limites de séries, voire de groupes. Ses tracés sont exécutés plus rapidement et le nombre de fosses et d'analyses peut être diminué de moitié, sans que la précision en souffre, bien au contraire. Compte tenu du coût des levés géomorphologiques eux-mêmes, des économies variant de 20 à 50 % peuvent être réalisées sur l'étude pédologique.

b) Études agronomiques. Certaines des possibilités du milieu naturel sont mises en évidence par la carte géomorphologique, qui fournit directement des données utilisables pour l'établissement des cartes de classification des terres : nature des terrains, zones inondables, microtopographie.

Les secteurs soumis à des phénomènes d'érosion sont également indiqués (ravinement, déflation éolienne, etc.). Il est facile d'étudier alors, en accord avec les indications dynamiques fournies par l'étude géomorphologique, les mesures à prendre pour arrêter ou combattre les phénomènes nocifs. Par exemple, notre étude du delta du Sénégal a mis en évidence les diverses origines du sel qui rend incultivables la plupart des terres. Nous avons pu établir l'importance du saupoudrage éolien sous l'effet de l'alizé, en saison sèche, à partir des sebkhas du nord-ouest du delta et proposer une méthode simple et peu coûteuse pour neutraliser le phénomène.

c) Études de travaux. Les indications que peut déjà fournir la reconnaissance sont développées et précisées, au besoin au moyen d'études détaillées spéciales. Par exemple, dans le delta du Sénégal, une carte géomorphologique au 1/20 000 a été levée par P. Michel pour l'édification du barrage de Dagana et l'installation des ouvrages de distribution des eaux. Elle a permis de mettre en évidence un microrelief qui, habilement utilisé, a permis une économie de 20 % dans les frais de terrassement. En effet, des faisceaux de levées anciennes, renforcés en certains endroits, permettent de protéger les casiers rizicoles et d'installer les canaux d'amenée, tandis que les marigots de vidange de cuvettes, curés, rectifiés et débarrassés de certains bouchons, peuvent servir d'axes de drainage.

Dans le projet du lac Faguibine (Soudan), la carte géomorphologique a mis en évidence un système de défluents complexe et permis de choisir des sites de barrages et de digues avantageux, sans levé topographique détaillé. Celui-ci a pu être limité à des profils dans les secteurs critiques. La carte a également fait ressortir les facilités d'approvisionnement en matériaux pour la construction d'ouvrages en terre.

L'étude dynamique qui accompagne la carte peut être poussée facilement jusqu'à un plus grand degré de détail pour rechercher des sites pour des installations (agglomérations, ports, prises d'eau), afin qu'elles présentent toutes les conditions souhaitables de stabilité et qu'elles n'aient pas à souffrir des actions naturelles.

Des économies considérables sont ainsi réalisées, qui s'ajoutent à celles procurées dans les domaines des études pédologiques et agronomiques.

Les études géomorphologiques ne sont pas très onéreuses. Pour des cartes détaillées, avec tous les travaux annexes de laboratoire et d'analyse dynamique, leur coût dépasse rarement un demi dollar l'hectare. De la sorte, leur rentabilité est très élevée et elles permettent souvent des économies dépassant deux à trois fois leur coût. De tels rendements sont d'ailleurs plus facilement atteints dans le cas d'équipe ayant pris l'habitude de travailler systématiquement avec l'aide de la géomorphologie, car, comme toute technique nouvelle, un apprentissage est nécessaire pour savoir l'utiliser à bon escient et lui faire rendre le maximum.

C'est pourquoi nous allons indiquer de quelle manière il nous semble possible d'organiser la meilleure programmation des études géomorphologiques.

PLACE DE LA GÉOMORPHOLOGIE DANS L'ORGANISATION DES PROGRAMMES

Il faut tenir compte de la taxomonie scientifique si nous voulons que notre organisation des recherches revête le maximum d'efficacité, condition indispensable d'un rendement économique élevé.

Le travail du géomorphologue s'effectue sur le terrain et au laboratoire. Comme toutes les recherches de terrain, il doit s'appuyer sur des documents de base. Les plus utiles sont les photographies aériennes, beaucoup plus riches que les cartes pratiquement irremplaçables. On en tire le maximum en les examinant sur le terrain, ce qui garantit contre toute erreur d'interprétation. Elles servent alors à interpoler les contours d'unités reconnues et définies, en profitant des facilités maximales de parcours, ce qui permet de gagner un temps considérable. Lorsque les cartes manquent, les photos aériennes peuvent servir à transcrire les levés, au moyen d'encres de couleurs vives (rouge notamment). On peut alors, sans perdre aucunement la précision, reporter plus tard ces levés sur des cartes définitives ou des mosaïques compensées. Nous avons opéré ainsi pour le delta du Sénégal.

Il est hautement préférable que le géomorphologue puisse disposer conjointement de mosaïques et des paires stéréoscopiques, indispensables pour l'étude du microrelief et pour les régions densément couvertes de végétation. Il peut alors laisser celles-ci à sa base et s'en

servir comme fond de carte en dessinant sur kodatrace ou sur n'importe quel papier similaire.

Le levé aérien doit précéder l'intervention du géomorphologue.

Les reconnaissances doivent être confiées seulement à des géomorphologues spécialement entraînés et ayant une très haute qualification professionnelle. Cette opération, en effet, est décisive, car elle joue un rôle dans l'établissement des avant-projets et dans la mise en train des études détaillées. Une erreur à ce stade a des répercussions très importantes pour la durée et le coût des études.

Une partie au moins des reconnaissances aboutissant à un parcours systématique de toutes les régions présentant un intérêt doit être effectuée en groupe. Le géomorphologue aura intérêt à accompagner l'agronome, l'ingénieur et le pédologue. La présence, dans l'équipe, d'un écologiste, présente habituellement un grand intérêt à condition qu'il s'agisse de quelqu'un pratiquant la cartographie géobotanique.

Comme les deltas sont des accumulations détritiques essentiellement quaternaires, le géomorphologue est beaucoup mieux armé que le géologue pour leur étude, et, sauf cas exceptionnel, la participation du géomorphologue rend inutile le recours au géologue. Celui-ci sera consulté seulement s'il se pose des problèmes de structure profonde ou de recherches minières. Cependant, des connaissances précises sur la géologie du bassin, principalement sur les faciès des roches et sur les formations superficielles, sont indispensables. Le géomorphologue aura intérêt à les acquérir au moyen de la littérature, complétée par quelques voyages rapides, avec récolte d'échantillons. Ceux-ci seront destinés à préciser l'origine des formations détritiques et, par exemple, à distinguer les accumulations marines et fluviales. Il sera bon de placer ce travail juste à la fin de la reconnaissance.

Étant donné l'importance des conditions géomorphologiques, il est indispensable d'associer le géomorphologue principal du projet aux discussions techniques visant à définir une politique d'aménagement et à établir les avant-projets.

Les levés géomorphologiques détaillés sur le terrain doivent précéder les études pédologiques et agronomiques auxquelles ils servent de point de départ. Ils doivent donc être inclus dans la toute première tranche des études détaillées, en même temps que les mesures climatiques, hydrologiques ou océanographiques.

Il y aura intérêt à ce que l'agronome et le pédologue effectuent des parcours systématiques de la région avec le géomorphologue juste à la fin de la phase des levés. D'une part, ils prendront connaissance de ce qu'ils peuvent attendre de la géomorphologie et se « feront l'œil » dans ce domaine, ce qui est indispensable, d'autre part ils pourront formuler des critiques et des desideratas dont il sera encore possible de tenir compte.

Après cette phase des levés, l'équipe de levé devra rentrer au laboratoire, quitte à ce qu'un des membres reste sur place afin d'assurer la liaison avec les autres spécialistes. Au cours d'une seconde phase du travail, elle partagera son temps entre : l'étude des échantillons récoltés (en collaboration avec le personnel hautement spécialisé de laboratoire) et le contrôle de la mise au net du dessin définitif des levés (qui exige, auprès des cartographes, la présence de quelqu'un ayant participé aux levés).

Le travail de laboratoire ne pourra généralement pas se faire dans la région des levés. En effet, les équipements sont importants et il faut pouvoir recourir à l'aide d'un personnel varié hautement spécialisé. De telles conditions ne sont réalisées que dans un tout petit nombre de grands centres de recherche. Il sera nécessaire de recourir à eux.

Par contre, la partie dessin pourra être réalisée sur place ou à proximité. Une liaison étroite sera toutefois nécessaire avec l'imprimerie, car l'impression de ces cartes en couleurs complexes est un travail très précis et délicat qui nécessite un contrôle minutieux.

Une fois terminé le travail de laboratoire, une nouvelle série de tournées sur le terrain sera nécessaire afin de contrôler ou compléter certains points. Elle servira également à résoudre les points apparus obscurs lors de la mise au net des cartes. Le dessin définitif de celles-ci sera alors terminé. Ces tournées permettront éventuellement de présenter les levés sur le terrain aux divers spécialistes qui les utiliseront. Cela est exrêmement important si l'on veut que l'étude géomorphologique serve au maximum.

Pendant la phase de préparation de l'impression des cartes et pendant leur impression, forcément longue à cause des couleurs, l'équipe terminera la rédaction de la notice, commencée déjà lors des études de laboratoire.

Pour les recherches importantes, il sera bon qu'un géomorphologue reste sur place pendant la phase ultérieure, comme nous l'avons fait pour le delta du Sénégal. Il servira de conseiller permanent aux autres spécialistes et se livrera aux études de détail complémentaires rendues nécessaires par l'élaboration des projets ou par la mise en train de certains travaux.

Il y aura toujours intérêt à ce qu'un géomorphologue puisse accompagner les équipes pédologiques lors de leurs travaux de levés. Il pourra les guider utilement, répondre aux questions et profiter des fosses ouvertes pour compléter l'étude géomorphologique ou la corriger sur certains points. Dans certains cas, il est très utile que les échantillons étudiés du point de vue pédologique le soient simultanément, aussi, du point de vue géomorphologie. Une meilleure coordination est ainsi assurée et le rendement est amélioré.

Les nouvelles conceptions de la géomorphologie lui permettent donc de répondre maintenant à bien des questions que se posaient les pédologues, les agronomes et les ingénieurs. Les réponses qu'elle peut leur fournir leur permettent d'effectuer leurs tâches dans de meilleures conditions de sécurité intellectuelle et technique et avec un rendement accru. C'est pourquoi

le recours aux méthodes géomorphologiques s'étend rapidement de nos jours. La principale difficulté est la relative rareté des spécialistes qualifiés, conséquence du caractère récent de l'évolution méthodologique qui a donné naissance à la géomorphologie appliquée. Mais certains organismes, comme le Centre de géographie appliquée, qui a une très riche expérience dans ce domaine, sont ouverts aux boursiers étrangers et organisés pour leur donner la formation nécessaire. Chaque année, son laboratoire de géographie physique en forme une dizaine.

Summary

The place of geomorphology in studies of the development of tropical deltas (J. Tricart)

The geomorphology of tropical deltas is determined by a complex combination of factors: the glacio-eustatic fluctuations of the sea level—a world-wide phenomenon; subsidences, often disparate even within the confines of the delta; the Quaternary fluctuations of the paleoclimate in the river basin, which are to some extent on a zonal scale but also vary locally; the peculiarities of the interplay of mutually antagonistic shoreline and fluviatile processes which vary from point to point of a given delta and over a period of time.

Modern geomorphology has satisfactory methods for the analysis of this combination of factors, which are presented, notably, in the form of detailed geomorphological maps. These maps, using the J. Tricart-CGA system, show the following: (a) the nature of the materials outcropping or lying near the surface; (b) the genetic nature of the land forms, treating each as a morphogenetic unit (alluvial levees, "slack water settling areas", secondary deltas at breaches in the levee, mangrove swamp shorelines, etc.); (c) certain topographic characteristics of these land forms not clearly shown on the topographical base (height of undercut banks, for instance); (d) the ages of land forms and, in the case of those of ancient origin, the age of the various changes they have undergone since their original formation (e.g., degradation of ancient alluvial levees by subsequent wind deflation).

Thus a picture is presented from which a landscaper's dynamical morphology can be grasped. Its bases are field-work (with the intensive use, on the ground, of air photographs) and systematic laboratory study of samples (genetic identification of land forms, determination of processes, dating of accumulations, alterations, etc.). Its possible uses are the following:

Soil maps: the detailed geomorphological map is the base for soil surveys, as demonstrated by the writer as long ago as 1953-1954 in the Senegal delta. The over-all economies obtainable by this approach may amount to 50 per cent and considerable time is saved.

Agronomics: the map gives the agronomist directly usable data, notably on the inundation pattern, erosion, etc. The map also provides valuable information for the purposes of the ecologist.

Engineering: the map supplies information on the nature of land formations and deposits of raw materials (e.g., for the building of earth dikes or dams), and on the process currently at work (undercutting, sand movements on beaches or under the action of the wind, etc.), it allows defences against dangerous processes to be planned, permits sites for engineering works and communication routes to be chosen and irrigation and drainage works to be adapted to the natural conditions—a major source of economies (20 per cent of embanking costs for the 50-hectare rice plantation at Rosso, Mauritania).

It is for this reason that our methods are being gradually adopted in a growing number of countries.

Discussion

H. T. Verstappen. The geomorphological studies treated in the paper deal particularly with the relation to pedology (soil science) and thus particularly stress the "static" aspect of geomorphology, viz., mapping of geomorphological phenomena. The engineers engaged in delta studies often have different needs and are particularly interested in the "dynamics", the changes in the phenomena observed. They want to know the processes of the past and present together with their effects, so as to possibly predict the future developments.

Could the speaker please elaborate on this dynamical aspect of geomorphology?

J. Tricart. Les cartes géomorphologiques, comme nous les concevons, donnent non seulement la dynamique des phénomènes passés, mais également celle de tous les phénomènes actuels. Notre systèmes figure ces derniers en *noir* alors que

les phénomènes passés sont figurés dans des couleurs variées qui indiquent leur âge. De la sorte, la dynamique actuelle ressort nettement. D'autre part, lorsque les phénomènes passés ne présentent pas d'intérêt, par exemple pour des travaux d'ingénieurs, nous faisons des cartes géomorphologiques qui sont limitées à la dynamique actuelle. Celle-ci est toujours figurée avec le maximum de détails compatibles avec l'échelle.

Pour les aménagements de cours d'eau, nos cartes sont généralement à l'échelle du 1/5 000. De la sorte, toutes les berges sapées, les bancs d'alluvions, les variations des types de lits fluviaux sont indiqués. La nature des dépôts est précisée. Nous distinguons également les accumulations nues et celles qui sont couvertes de végétation.

De la sorte, nos cartes satisfont aux exigences des ingénieurs.

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Comparative study on the geomorphology and flooding in the plains of the Cho-Shui-Chi, Chao-Phya, Irrawaddy and Ganges

Masahiko Ohya

INTRODUCTION

In 1962, at the request of the Economic Commission for Asia and the Far East (ECAFE), the governments of Japan, the Netherlands and the Republic of China organized the Expert Mission on Deltaic Areas. The mission, comprising experts offered by these countries, was organized to carry out field inspections and studies of several deltaic areas in the ECAFE region from November 1962 to February 1963.

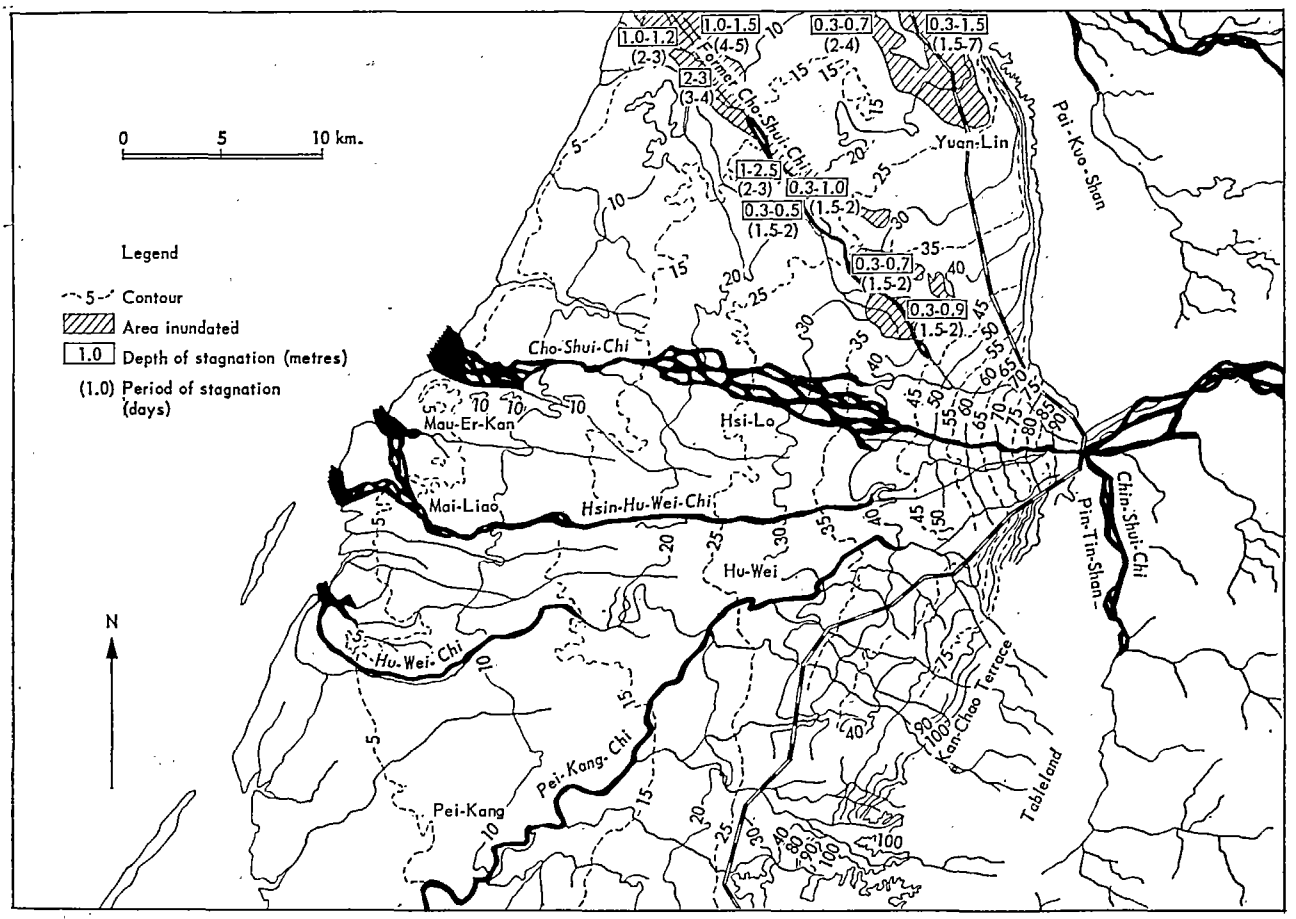

FIG. 1. Map showing the state of flooding in the Cho-Shui deltaic area.

The mission made field inspections of the Nobi delta in Japan, the Cho-Shui-Chi delta in China, the Chao-Phya delta in Thailand, the Irrawaddy delta in Burma and the Ganges delta in India and East Pakistan.

Being in charge of the work of the mission in the field of geomorphology I am able to report here on the comparative study of the geomorphology and flooding of the plains of the Cho-Shui-Chi, Chao-Phya, Irrawaddy and Ganges located in the tropical zone.

CHO-SHUI-CHI PLAIN

Upper reaches

The Cho-Shui-Chi originates on the steep slopes of the Ho-Huan mountain in Taiwan at an elevation of nearly 3,393 metres. The upper reach of the river, above the railway bridge near Linnei, has a steep gradient (19 in 1,000). The native rock of the area is mostly black, brittle and friable shale with some lateritic gravel layers. Because of the topography, nature of the rock, heavy rains and earthquakes, landslides are frequent and considerable quantities of sand and gravel are brought to the river. It is from the heavy sediment load carried by the river that it gets its name Cho-Shui-Chi, meaning "dirty water river".

Lower reaches

These form a large fan with its apex just below the Linnei railway bridge and with a radius of about 13 km. The ground surface at the apex is about 100 metres above sea level and the lower periphery about 40 metres. The fan is composed of sands and gravels deposited by the many diverging river channels, and the old Cho-Shui-Chi, the Hu-Wei-Chi, the Hsin-Hu-Wei-Chi (new Hu-Wei river) and the Pei-Kang-Chi are contained in its area (see Fig. 1).

The river bed is rising slowly but steadily, and there is a possibility that the Cho-Shui-Chi may change its course in the future.

Several levees extend from the fan to the west. The boundary of the fan and levee in the Cho-Shui-Chi is near Shu-Tze-Chio. Gravels are found in the river bed upstream of Shu-Tze-Chio but downstream almost all the dry river bed is formed by sand.

The lower delta of the Cho-Shui-Chi below Mao-Er-Kan is small. The ground elevation is from 1.7 to 10 metres and has a general slope of about 1.25 in 1,000. The soil is sandy and riverside sand-dunes have formed with the sediments brought down from the upper reaches of the river.

The sand-dunes located in Mai-Liao and San-Hsing are coastal sand-dunes formed along the former coastal line. The line where the villages Mai-Liao and San-Hsing are situated was the shoreline (Fig. 2).

Newly reclaimed paddy fields extend from that line towards the west. These fields have existed since 1932. From 1932 to 1957 the coastal line was extended by

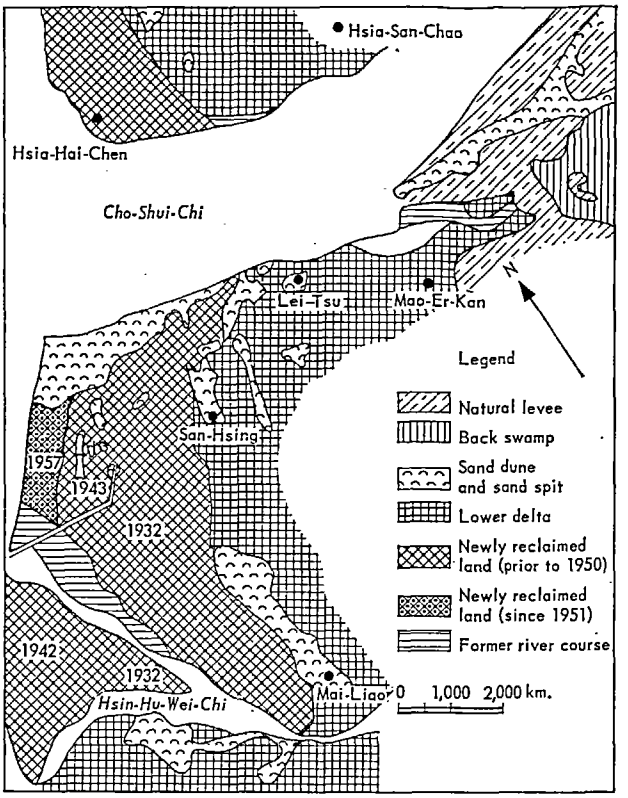

FIG. 2. Geomorphologic map of the estuary of the Cho-Shui and vicinity showing the classification of flood-stricken areas.

about 3.75 km. (approximately 150 metres in a year). This rate of seaward extension is the highest that I have noted in all the deltas I have surveyed.

The sea coast of the Cho-Shui-Chi delta is attacked by storm surges caused by occasional typhoons, but the damage is not too severe because the ground is high.

CHAO-PHYA PLAIN

Upper reaches

Four large rivers, the Ping, Wang, Yom and Nan, originate in the mountains of northern Thailand and combine to form the River Chao-Phya near the city of Nakorn Sawan.

For a distance of about 50 km. below Nakorn Sawan the Chao-Phya is confined to a single stream by the encroaching hills on either side. In the watershed above these narrows are several basins in which is deposited a large part of the debris carried by the streams.

Lower reaches

The Chao-Phya plain comprises the triangular-shaped plain of Thailand from Chainat to the Gulf of Thailand. Its base extends from the Mae-Klong river to the Bang

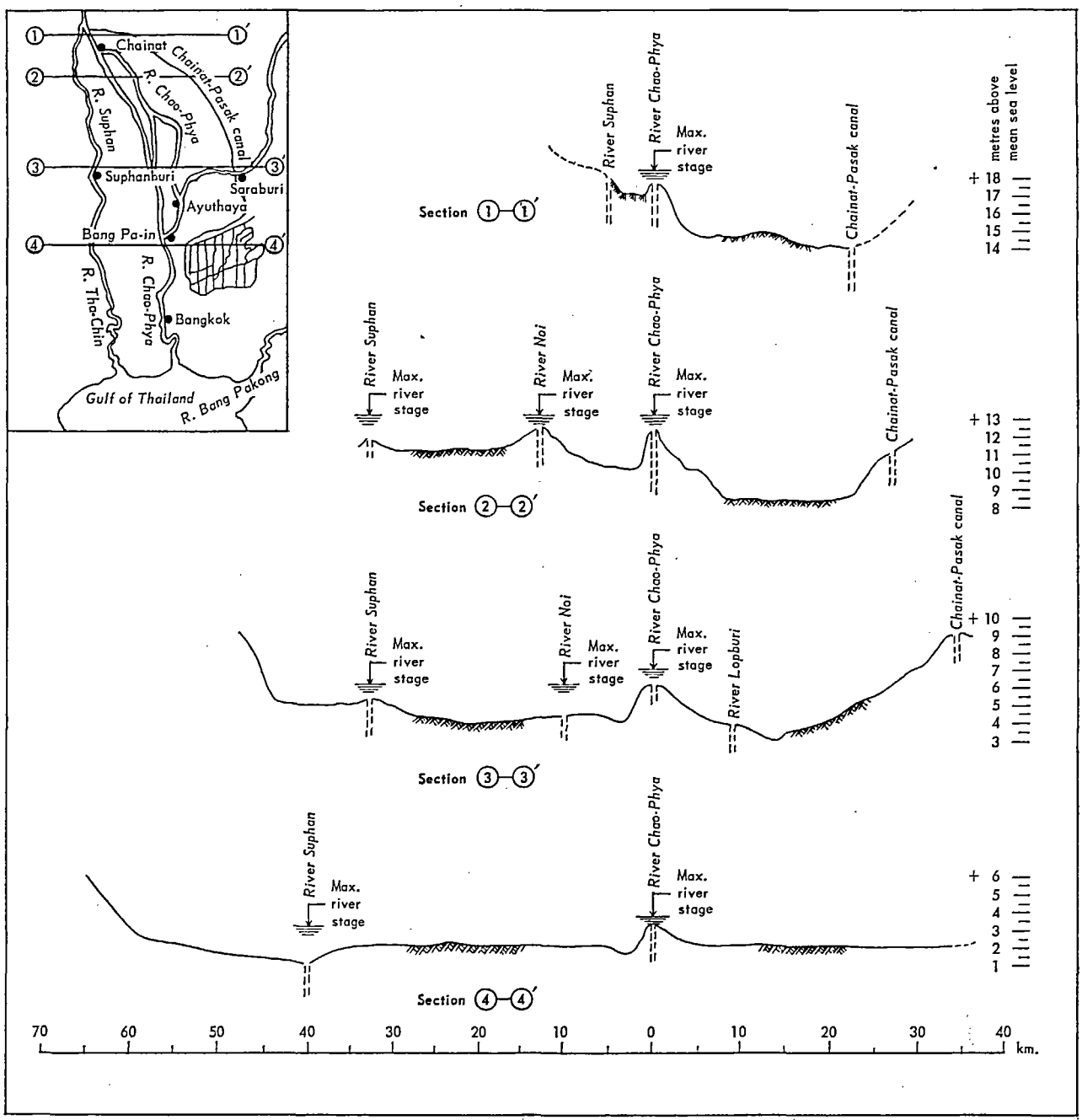

FIG. 3. Cross sections of the Chao-Phya deltaic area.

Pakong river and includes either the Tha-Chin or Suphan river.

Below the narrows, in the vicinity of Chainat, the river branches into several distributaries, the principal ones being the Suphan, the Noi, the Chainat-Pasak main canal and the Chao-Phya.

The predominant feature of the deltaic area is that, although the fan can scarcely be seen, the four distinct levees formed by the Chao-Phya and its distributaries are apparent.

The largest of these levees extends along the Chao-Phya from Chainat to Ayuthaya, a distance of about 145 km. At its head the levee is about 17 metres above mean sea level and at the lower end it is about 2 metres. The relative height of the levee with respect to adjacent terrain is from 2 to 3.5 metres in the upper portion. The width ranges from 5 km. in the upper portion to 8 to 10 km. in the lower portion. In addition to these four principal levees there are many smaller levees which mark the course of former river channels (Fig. 3).

Back swamps occupy the areas between the levees. Rain and flood-water stagnate in the back-swamp areas for several months of the year; these areas are therefore mostly used for paddy fields. Stagnation in these areas reaches a depth of about 4.5 metres. In the deepest areas cultivation of floating rice is a well-developed practice. Virtually the whole plain is covered by flood-water during the rainy season, which makes extensive rice production possible (Fig. 4).

The lower delta extends from the city of Ayuthaya to the south and is between 0.30 and 2 metres above sea level; the lower periphery shows a gentle slope of about 0.02 per mille.

Due to these gentle slopes and the comparatively mild nature of the floods fine sediments enter the area, hence the soils are generally of a finer texture and heavier than those found in the Cho-Shui-Chi delta.

In the Chao-Phya delta the average annual precipitation at Ayuthaya, in the heart of the rice district, is about 1,270 mm., and the rainfall during the paddy-growing season is only about 1,000 mm. The average rainfall requirement for rice is around 1,500-1,800 mm., the deficiency being made up by the river which, originating in the upper reaches, takes roughly from one to three months to arrive at the deltas.

The small variation of the flood-water between dry season and wet season in the lower delta is about 30 cm.

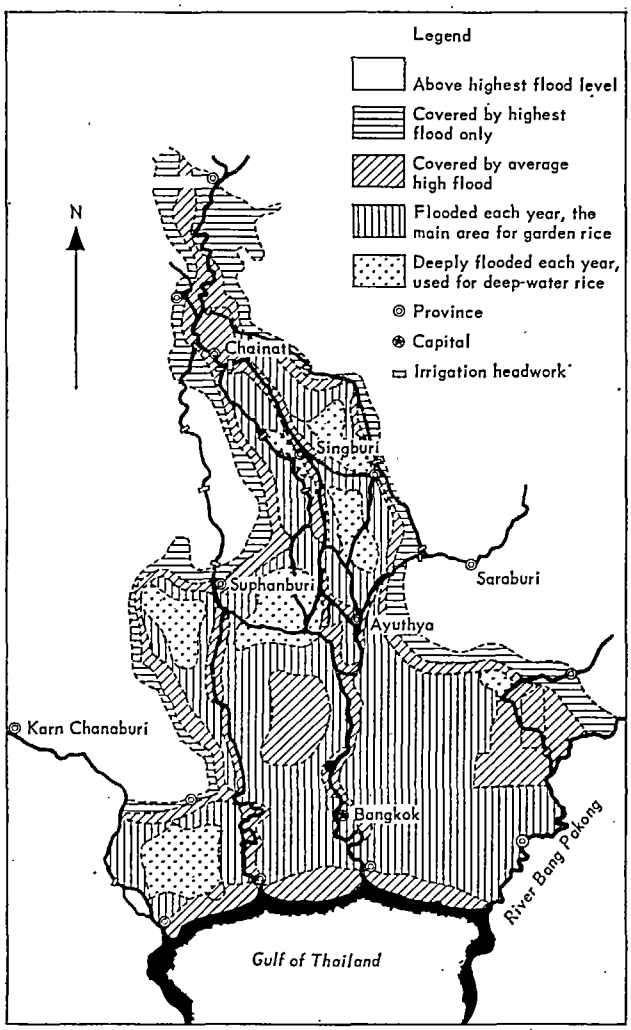

FIG. 4. Map showing depth of flooding.

IRRAWADDY PLAIN

Upper reaches

The River Irrawaddy has its origin in the mountains of northern Burma. It is joined by its major tributary, the Chindwin, near the city of Pakoku.

The upper watersheds of both streams are mountainous, the slopes are steep and total rainfall is high with many localized torrential downpours. Surface erosion contributes large amounts of sediment to the streams.

The sediment load of the main stream of the Irrawaddy (32 million tons at Mandalay) is smaller than that of the Chindwin (109 million tons at its mouth).

This is because the main stream of the Irrawaddy has several basins along its course, i.e., the Myitkyina, Bhamo, Katha and Mandalay basins. When there is a basin along the course of a river the greater part of the debris collected in the upper reach above the basin is deposited in it.

Middle reaches

The middle reaches of the Irrawaddy above Myanaung comprise the so-called "dry zone". The long, dry season and the violence of the few rainstorms make this a zone of powerful erosion approaching Bad Lands in character. A great part of the sediment load is supplied by erosion in the dry zone.

Lower reaches

The apex of the Irrawaddy plain is at Myanaung. It extends 290 km. to the south and has a maximum width of about 240 km. There are many distributaries in the area.

A noticeable feature of the area is its low altitude. Except for a few scattered hills and terraces the total area of 31,000 sq. km. is less than 16 metres above mean sea level. About 5,300 sq. km. are below high spring-tide level.

The fan is scarcely distinguishable but the levees are large in the area and may be seen between Myanaung and Yandoon. Here the rivers are incised and their banks are from 6 to 9 metres high.

This upper part of the area comprises a fine sand or silt layer; the thickness at Henzada is between 7 and 8 metres. Stratification in the layer indicates successive flood deposits.

Flooding in the Irrawaddy delta results partly from upper river discharge and partly from local rainfall. At Bhamo the flood levels in the river correspond closely to the precipitation, both peaks occurring in July. Because of the time required to flow down the channels, floods from the upper river arrive at the delta roughly one month after the peak rains to find the area already suffering from floods due to local rains.

Because of the heavy rainfall, torrential showers and large tidal range, erosion is common in the deltaic area, hence there is little vertical accretion to the land level; however, the area is extending towards the sea at an annual rate of about 50 metres The sand-bars formed near the sea-shore are fixed by vegetation so that the lagoon behind each bar is gradually filled with mangrove and rises above the sea level.

The southern extremities of the Irrawaddy delta are forested with species best suited to the conditions of soil, flooding and salinity of the water.

GANGES PLAIN

The Ganges plain is formed by three large rivers: the Ganges, Brahmaputra and Meghna.

Upper reaches

The Ganges and Brahmaputra originate in the perpetual snows of the great Himalayas and drain a large part of both the southern and northern slopes of that range. Thus these streams are fed by snow melt and the monsoon rains of the lower reaches. The Meghna rises in the Luhai hills in Assam at a much lower elevation but in an area subject to intense monsoon rains. Owing to the rugged topography and abundant rain, erosion is intensive.

There are distinct fans at the foot of the Himalayas and large levees in the Hindustan plain.

Lower reaches

The deltaic area can be considered roughly as the area lying south of the Rajmahal hills and the Shillong plateau and extending to the shoreline of the Bay of Bengal. In the Sunderbans there is an extensive and very complicated system of interconnected distributaries.

The presence of numerous levees indicates that there were many major and minor changes of stream channels in the past. Most prominent are the levees extending from Calcutta to the south-east which show a major shift of the Ganges from west to east. This shift was due to crustal movement with the ground dipping in the eastern part of the Ganges plain. Thus the western part of the delta, in India, appears to be older than the eastern part, in Pakistan.

Some differences in the topography of the eastern and western parts of the Sunderbans are quite noticeable. The levees in the western part are higher than in the eastern part.

An east-west section through the delta at latitude 22°50′N. shows that the height of levees progressing from west to east is 4.8 metres for the Betna river, 4.5 metres for the Kobadak river, 3.0 metres for the Bhaddra river and 2.4 metres for the Bhairab river.

In the western part the creek banks are more pronounced. The small side-drainage channels are more deeply incised in the western part, while the upper reaches are wider in the eastern part. The natural vegetation and soil conditions in the eastern part show that the fresh-water influence is greater there than in the western part. These differences show an interesting relationship between erosion and deposition that deserves further study.

The coasts of the Sunderbans are attacked by storm surges caused, now and then, by cyclones.

Résumé

Étude comparative de la géomorphologie et des inondations dans les plaines du Tcho-Chui-Tchi, du Tchao-Phya, de l'Iraouaddi et du Gange (Masahiko Ohya)

Il existe des différences régionales nettes du point de vue de la géomorphologie et des inondations entre les plaines du Tcho-Chui-Tchi (Taïwan), du Tchao-Phya (Thaïlande), de l'Iraouaddi (Birmanie) et du Gange (Inde et Pakistan-Oriental).

1. Dans la plaine du Tcho-Chui-Tchi, il y a un grand cône de 13 kilomètres de rayon, mais la levée naturelle et le delta sont petits. Au contraire, le cône est à peine visible, mais la levée naturelle et le delta sont grands dans les plaines du Tchao-Phya et de l'Iraouaddi.
2. La granulométrie du sol des plaines du Tchao-Phya, de l'Iraouaddi et du Gange est presque toujours argileuse, mais elle est sableuse dans la plaine du Tcho-Chui-Tchi.
3. On peut distinguer dans une plaine deltaïque trois parties : la levée naturelle et la dépression latérale marécageuse, le delta supérieur et le delta inférieur.

   La variation du niveau de l'eau entre la saison sèche et la saison humide est la plus grande dans la levée naturelle et dans la dépression latérale. La crue est moyenne dans le delta supérieur. Le flux marin domine dans le delta inférieur.
4. Sur la levée naturelle, l'inondation est courte et faible. Mais dans la dépression latérale, elle est longue et forte. Dans les dépressions latérales du Tchao-Phya,

de l'Iraouaddi et du Gange, la crue dure plusieurs mois.

La hauteur de la crue dans les dépressions latérales est proportionnelle à la hauteur de la levée naturelle. Elle est plus grande vers l'amont de la plaine que vers l'aval. Dans la plaine du Tchao-Phya, elle peut atteindre jusqu'à 4,5 mètres environ. Dans les zones les plus inondées, on cultive le riz flottant.

5. La pente des deltas est très faible, sauf dans le cas du Tcho-Chui-Tchi. Par exemple, la pente du delta du Tchao-Phya n'est que de 0,02 pour 1 000.
6. Dans le delta inférieur du Gange et de l'Iraouaddi apparaît une forêt épaisse (mangrove, etc.). Les terres sont mises en culture dans le delta inférieur du Tcho-Chui-Tchi. C'est le front du delta du Tcho-Chui-Tchi qui progresse le plus rapidement sur la mer.
7. Sauf dans le cas du Tcho-Chui-Tchi, la crue prend approximativement de un à trois mois pour parvenir du cours supérieur du fleuve dans le delta. Les pluies qui tombent dans la plaine seraient insuffisantes pour la culture du paddy. L'eau des crues en provenance du cours supérieur du fleuve a donc une importance décisive pour ces régions.
8. Dans la plaine du Tcho-Chui-Tchi, la crue est très dangereuse pour la population. Au contraire, dans le cas des autres bassins fluviaux, l'eau de crue est une bonne eau d'irrigation.
9. Le littoral du delta du Tcho-Chui-Tchi est attaqué par les fortes marées que provoquent parfois les typhons; mais les dégâts sont limités par le niveau élevé du sol. Il n'y a pas de fortes marées sur la côte du delta du Tchao-Phya. La partie inférieure des deltas du Gange et de l'Iraouaddi est attaquée de temps à autre par les fortes marées que provoquent les cyclones.

Discussion

V. N. Nagaraja. By way of information, the western sea face of the Bengal delta, off the Hooghly, has not shown any extension during the last century. It is understood that, on the eastern part, some extension has taken place and it would be interesting to have information on it.

Regarding studies with coloured sand, etc., for studying sand movement, experiments have been made in the Hooghly for studying the pattern of silt movement in shoal areas and results have been published. Similar experiments have been made off the Bombay and Cochin coasts for optimizing dredging efficiency.

V. J. Chapman. Has any information been obtained about the rate of sedimentation in any of the deltas? For example, elsewhere information has been obtained by the use of coloured sands and other means.

Boonchob Kanchalanak. To answer the question raised by Dr. Chapman as to what extent the delta in south-eastern Asia extends seawards: the submerged delta extension of the Chao-Phya in Thailand, for example, varied from 250 to 500 metres during the period covering the last twenty years.

The use of aerial photographs in delta studies

H. Th. Verstappen

INTRODUCTION

The perfection of aerial survey techniques has resulted in an improved quality of aerial photographs and the universal use made nowadays of these techniques has yielded an increased understanding of the modes of application in the various scientific disciplines. Aerial photographs have thus become invaluable in delta studies, because they reveal a variety of terrain features which are imperceptible in the field, and which cannot, or only with great difficulty, be obtained by other means. It goes without saying that field checking of the photo-interpretation is always essential and it should furthermore be understood that this technique is not in itself a panacea for the solution of the problems related to delta development. The photo-interpretation should be carried out in conjunction with numerous other types of research. It is only by co-operation between experts in sedimentology, geomorphology, hydrology, vegetation, etc., that the problems of humid tropical delta areas can be solved.

GEOMORPHOLOGY AND AERIAL PHOTOGRAPHIC STUDIES OF DELTA AREAS

Criteria for interpretation of the aerial photographic image are of three main types: grey tone, relief and associated features (vegetation, land use, etc.). The third group of criteria can be identified on the photographs on the strength of grey tone, relief and/or pattern, and it therefore depends partly on the other two groups.

Grey tone is an important factor which may, for example, yield information about the material in suspension near a river mouth and its displacement by currents, about subaquatic shoals and about the nature of non-vegetated flatland areas (mud flats, etc.). Furthermore it has a much more general significance in photo-interpretation for the indication/delimitation of almost every phenomenon that would otherwise be invisible or could only be appreciated on the strength of its relief characteristics. Relief is a fully independent factor and is as important as grey tone. Essential information can be derived from it and for this reason stereoscopic study of the aerial photographs is indispensable. This is also true for the largely flat deltaic regions, because the micro-relief and the height of the vegetation may yield a considerable amount of information. Photo-mosaics of flatland areas can be constructed from alternate photographs to enable a stereoscopic study to be made. Otherwise they only serve to obtain a general view of the delta, which is of little use in photographic evaluation.

It will be evident from the above that geomorphology plays an important role in photo-interpretation. The most conspicuous phenomena of the three-dimensional image obtained are land forms. Grey tone characteristics may contribute to the delineation of their horizontal extent, but relief certainly is the prime criterion. Geomorphological phenomena are usually clearly visible and as a result they can often be mapped from the air with greater accuracy and in more detail than would otherwise be possible. Such precise delineation of the various parts of a delta and the indication of former river courses, levees, etc., is already very useful for the soil survey of the area and for a number of other purposes. This "static" approach of delineating areas of comparable geomorphological origin and development deserves a place for itself, however. The geomorphological understanding of the genesis, relative age, etc., of the mapped features often clarifies their physical characteristics and also their potential utilization

The "static" approach is, particularly in delta studies, only one aspect of the geomorphological studies. The "dynamic" interpretation of the observed phenomena is often more important. The natural levees and other phenomena indicating abandoned river courses, former shorelines, beach ridges, located inland, should be arranged in chronological order, whenever possible. This will permit an insight into the delta formation

and the factors influencing it. Many of these factors and processes will still be active and the extension of their effects into the future may point to the developments to be expected. This type of work may contribute substantially to the understanding of the delta, of its historical development and of the processes governing its former, actual and future changes. This is particularly important for engineering purposes, even more so because the difficulty of access to many delta areas in the humid tropics makes other methods of investigation difficult. Quantitative interpretation of recent changes in position of the coastline and of the various distributaries is possible if several photo coverages can be obtained, taken at sufficiently long intervals.

The growth of the delta of the River Solo (eastern Java) is given as an example of such a quantitative approach. Two editions of the 1 : 50,000 topographical map showing the coastline as surveyed respectively in 1915 and 1936 and an aerial photographic coverage dating from 1943, form the basis of the following considerations. The seaward growth of the delta in the period 1915-1936 amounted to 3,600 metres and for the period 1936-1943 to 800 metres. Several minor changes in the river channels occurred in these periods, influencing the distribution of the sedimentation. It is thus relevant to study the areal growth instead of the linear values of accretion. This amounted to 8 sq. km. (approx.) for the first period and to 1 sq. km. (approx.) for the second. The decrease in sedimentation rate can be largely accounted for by the increasing depth of the area of deposition. The estimation of the total quantity (volume) of the deposited material cannot, of course, be derived from the aerial photographs alone, but if the depth contours of the existing chart are taken into consideration, such volume estimates are feasible.

Much more detailed studies of this kind are also possible. Large-scale photography (1 : 5,000) of the Dutch coast is being made at regular intervals to determine the changes in position of the high-tide mark and of the foot of the dunes.

More interesting and of a wider field of study are aerial photographic studies of deltas, centring on the genetic understanding of the dynamics and the geomorphological processes of sedimentation, etc. These can relate to a great diversity of factors. Studies on the formation of alternating beach ridges and swales under the influence of the ever-changing equilibrium between river work and marine abrasion may be mentioned in this relation. Studies on the influence of the changes in the position of a river mouth on accretion and abrasion of the coast yield quite interesting results which can also be used for predicting coastal changes provoked by man-made changes of a river mouth. The effects of a man-made change of a river mouth on the distribution of accretion and abrasion are illustrated by the case of the River Tjidurian (western Java), where a new river mouth was made in 1927 for irrigation purposes. Its location is 4.5 km. to the west of the old mouth. It appeared from aerial photographs that approximately 2.5 km. accretion occurred in 18 years' time, whereas the distortion of the balance between deposition of river deposits and wave action has resulted in serious recession of the coastline in the surroundings of the old river mouth. As a result the mangrove belt bordering the coast has completely disappeared and the dikes surrounding the fishponds located further inland were destroyed by the waves. These were unforeseen consequences of this engineering project.

Similar developments are often encountered as a result of natural, geomorphological processes. A river in flood occasionally breaks through its natural levee and it may then take another course instead of resuming its original one as, for example, did the River Tjitarum. The effect of such changes of river courses on coastal development are traceable in many localities. The abandoned parts of the delta will be abraded, and the coastline will gradually develop a smoothly curved outline. The more recent the displacement of the river course, the less pronounced will these coastal characteristics be. The Tjisadane and Tjitarum deltas are good examples. River piracy may also be the cause of such coastal changes. This is the case, for example, in northern Sumatra where the River Peusangan originally debouched near the town of Bireuen but later took a more easterly course along the foot of the ridge stretching from east to west which it formerly traversed. The old delta is largely abraded and a straight coastline is now present. A new delta is formed farther to the east.

Changes in sea or lake level also have a large impact on the development of deltas, the result of which can well be studied from the air. Slow subsidence of a delta under its own weight and tectonic movements are not always easily distinguished from the effects of sea-level changes. It is, however, possible in many cases to indicate the role played in delta growth by young differential crustal movements of local importance.

It appears from a comparative study of old and new maps, and of recent aerial photographs, that the growth near the mouth of the River Digul (New Guinea) is rather limited, whereas rapid seaward displacement of the coastline occurs farther to the south near Cape Valsch. This is at first sight rather astonishing. It is due to the occurrence of a zone of recent uplift which passes through Cape Valsch. Therefore, accretion there has no direct relation to the sedimentation of the Digul. Drowned forests located further inland indicate areas of recent subsidence where deposition of Digul sediments occurs. The delta growth near the river mouth is thus diminished.

A zone of subsidence running east to west can be traced in the Mamberano delta (New Guinea) on the strength of the distribution of mangrove and freshwater vegetation types. Lake Rombebai, located in the eastern part of this zone is traversed by the River Mamberano. The parts of its levee located in this

sinking zone are, of course, particularly apt to break through during floods. A "delta in a delta" is thus formed in Lake Rombebai. A belt of mud volcanoes occurs to the south of this belt. Shoreline mapping and the study of off-shore features is quite a different aspect of aerial delta studies.

PHOTOGRAMMETRIC ASPECTS

The delineation of usually shallow, delta coasts on aerial photographs is often fraught with difficulties because, on panchromatic film material, it is difficult to decide whether a shoal or sand-bank is just emerging or is still covered by a thin layer of water, due to the limited range of grey-tone variations. Infra-red photographs, taken at high tide, are excellent for delineation purposes, because the water surface then is rendered black. The disadvantage is, however, that underwater features of interest, such as material in suspension, the submarine continuation of natural levees, etc., cannot be seen on such photographs. The combination of infra-red photographs taken at high tide and colour photographs taken at low tide is the ideal solution to this problem.

Depth measurements make possible quantitative study, which can be done stereoscopically provided that the water is clear, the water surface is undisturbed by wind ripples or waves, and the sea bottom shows distinct tonal contrasts. Continuous strip cameras are useful for this purpose. Another method is in determining the distance between floats and their shadow on the sea bottom. Pots containing dyes in several colours, thrown from an aircraft, are also used. The water pressure controls the various colours and the area is photographed shortly afterwards. Densitometers have proved to yield unreliable results.

In turbid water measurements carried out about the landward decrease in wavelength or about the increase in velocity of the waves can be used. In the latter case the precise interval between the successive photographs should be known.

Current measurements are also attempted by aerial methods. Floats which are photographed at regular intervals are generally used for this purpose. Pots containing dyes may be used for estimating river discharges. The pots are automatically opened when they reach the bottom and the distance between the splash and the point where the dye reaches the surface is measured from the air. This distance depends on depth, average current speed and the (known) rate of ascent of the dye.

CONCLUSIONS

It is evident from the above that aerial photographic studies of deltas have three distinct aspects. The delineation of various parts and elements of the delta is the first aspect. It is important to unravel the history of the delta. The interpretation of the dissected older parts of the delta resembles interpretation of other degradational areas. Mapping of vegetation and land use in delta areas comes in the same group. Such studies can reveal useful information about the soil and hydrological conditions. Photo-interpretation of mangrove coasts is a particularly well-explored field.

The dynamic interpretation of deltas and delta coasts is the second aspect. A variety of processes, e.g., changes in river courses, variations in frequency or force of onshore winds, crustal movements, etc., play a role.

The third aspect is largely photogrammetrical. It includes, for example, mapping of shorelines and underwater features, determination of depth, etc. It is a particularly interesting approach in areas to which access is difficult.

These different types of aerial survey techniques can contribute to delta research in general, to coastal engineering studies and to the planning of an efficient land utilization of delta areas.

Résumé

L'emploi des photographies aériennes dans les études sur les deltas (H. Th. Verstappen)

Les photographies aériennes sont des auxiliaires précieux, notamment pour l'étude des deltas, car elles révèlent diverses caractéristiques du terrain qui sont imperceptibles au sol et qui ne peuvent être décelées par d'autres moyens ou ne peuvent l'être que très difficilement. Elles permettent ainsi d'établir une carte beaucoup plus exacte et plus détaillée des éléments géomorphiques qui constituent le delta. L'emploi des photographies aériennes aide donc beaucoup à comprendre la structure du delta, sa transformation au cours des âges, ainsi que les phénomènes qui régissent son évolution actuelle et future. Cela est particulièrement utile dans les deltas qui sont recouverts en grande partie par de la végétation ou dont l'accès est, pour d'autres raisons, difficile, comme c'est le cas de nombreux deltas de la zone tropicale humide. Il va sans dire que l'usage des photographies aériennes doit s'accompagner d'une vérification au sol de l'interprétation des photographies, ainsi que d'autres types de recherches (sédimentolo-

giques, hydrologiques, etc). L'examen stéréoscopique est toujours indispensable, même dans les régions deltaïques plates, car, si les photographies en microrelief ou obliques peuvent permettre d'obtenir une vue d'ensemble d'un delta, elles ne se prêtent généralement pas à l'évaluation photographique.

La délimitation des diverses parties d'un delta, le repérage des cours antérieurs du fleuve et des anciennes levées, etc., présentent déjà un grand intérêt (par exemple pour l'étude pédologique de la région), mais cette méthode « statique » ne devrait être considérée, surtout dans le cas des études sur les deltas, que comme une introduction à l'interprétation « dynamique » des phénomènes observés. Les levées naturelles et autres phénomènes indiquant des lits que le fleuve a abandonnés, ainsi que les crêtes de plages situées à l'intérieur des terres et marquant des positions antérieures du littoral, doivent être classés par ordre chronologique pour que l'on puisse se faire une idée de la formation d'un delta et des facteurs qui y jouent un rôle. Un grand nombre de ces facteurs sont encore agissants et l'extrapolation de leurs effets peut indiquer l'évolution à prévoir. Si l'on dispose de plusieurs séries de photographies prises, par exemple, à plusieurs années d'intervalle, on peut se livrer à une interprétation quantitative du déplacement du littoral et des divers bras du fleuve; c'est le cas notamment pour plusieurs fleuves de Java (Indonésie). On peut même procéder à des études quantitatives détaillées; il se fait actuellement, à intervalles réguliers, des photographies à grande échelle (1/5 000) de la côte néerlandaise afin de déterminer le déplacement de la laisse de haute-mer et du pied des dunes.

Il est souvent très difficile de délimiter, sur les photographies aériennes, les côtes deltaïques, qui sont généralement basses, car les photographies obtenues au moyen de pellicules panchromatiques ne permettent pas facilement, en raison du nombre limité des nuances de gris, de déterminer si un haut-fond ou un banc de sable émerge légèrement ou est encore recouvert par une mince couche d'eau. Les photographies aux rayons infrarouges prises à marée haute sont excellentes en pareil cas parce que la surface de l'eau est alors de couleur noire. Cependant, ces photographies ont l'inconvénient de ne pas indiquer des caractéristiques sous-marines intéressantes, telles que les matières en suspension, le prolongement sous-marin des levées naturelles, etc. La solution idéale consiste à combiner l'emploi de photographies aux rayons infrarouges prises à marée haute et celui de photographies en couleurs prises à marée basse. Une autre donnée quantitative qu'il est possible d'obtenir est la mesure de la profondeur. Dans l'eau claire, cette mesure peut se faire soit stéréoscopiquement, avec correction pour tenir compte de la réfraction, soit en déterminant la distance entre des flotteurs et leur ombre sur le fond de la mer. Dans l'eau trouble, il faut recourir à d'autres méthodes, comme la mesure des variations de la longueur des vagues à l'approche de la côte ou l'emploi de pots de peinture. On peut procéder aux mesures courantes en photographiant des flotteurs à des intervalles réguliers et connus.

Les études sur les deltas faites au moyen de photographies aériennes, qui ont généralement pour principal objet d'évaluer les forces en jeu, les processus géomorphologiques de sédimentation, etc., peuvent porter sur des facteurs très divers. Il faut citer à cet égard les études sur la formation alternative de crêtes de plage et de dépressions sous l'effet des variations continuelles d'équilibre entre l'apport fluvial et l'érosion marine. Les études concernant l'influence du déplacement de l'embouchure du fleuve sur la formation de la côte fournissent aussi des résultats très intéressants qui permettent de prédire les transformations du littoral provoquées par le déplacement artificiel de l'embouchure d'un fleuve; on en trouve des exemples dans diverses régions de Java et de Sumatra. Les variations du niveau de la mer ou des lacs influent aussi considérablement sur l'évolution des deltas et leurs effets peuvent fort bien être étudiés au moyen de photographies aériennes. Il n'est pas toujours facile de distinguer l'affaissement d'un delta sous l'effet de son propre poids et de mouvements tectoniques, des résultats produits par les variations du niveau de la mer. Mais il est souvent possible de déterminer le rôle joué dans l'expansion des deltas par les mouvements récents de la croûte terrestre. Une expansion due en grande partie à une récente élévation du terrain est signalée dans la région du Digul (Nouvelle-Guinée), alors que, dans cette même île, un affaissement local a été observé dans le delta du Mamberamo. Les méthodes fondées sur l'interprétation des photographies aériennes peuvent être utilisées pour les études sur l'aménagement des côtes et peuvent également servir à planifier une utilisation efficace des terres des régions deltaïques.

Discussion

G. A. Prowse. The use of aerial photographs could be considerably increased with the use of colour, for instance the colour of the water could be seen, presence of silt, etc., or whether dense plankton is present.

H. Boesch. In addition to what Dr. Verstappen said it should be pointed out that the following possibilities concerning film material exist: (a) ordinary black and white; (b) infrared; (c) colour; (d) false colour; and that, by a combination

of such films, aerial photographic interpretation can be greatly enhanced. Wherever possible the scientist should insist that in addition to (a) the films (b), (c), (d), alone or together, should be utilized in conducting aerial surveys.

KANOK PRANICH. I second the motion put forward by Professor Tricart that the symposium pass a recommendation that in the event of preparing aerial photographs of deltaic areas, the use of at least two different sets of films—black and white and infra-red—should be encouraged, as the value of an extra set of infra-red films would be far beyond the additional cost. It would help a great deal in the interpretation of the photographs.

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On the gradual shifting of the Ganges from west to east in delta-building operations

M. I. Chowdhury

From time immemorial it has been maintained that there has been a gradual eastward shift of the River Ganges from west to east, i.e., from the Bhagirathi-Hooghly to the present main course, the Padma-Meghna, with the Ichhamati, Jalangi-Mathabhanga, Gorai, etc., representing intermediate positions of the most important channels. Mythological sayings support this view but historical maps from that of Ptolemy (A.D. 150) to that of Rennel contradict the statement. (Some of them are shown in Figs. 1, 2). In all these maps, the Padma channel has been marked as the Great Ganges or Gange Majoris and the Bhagirathi-Hooghly channel as the Little Ganges or the Gange Minor. As all maps in those days were prepared

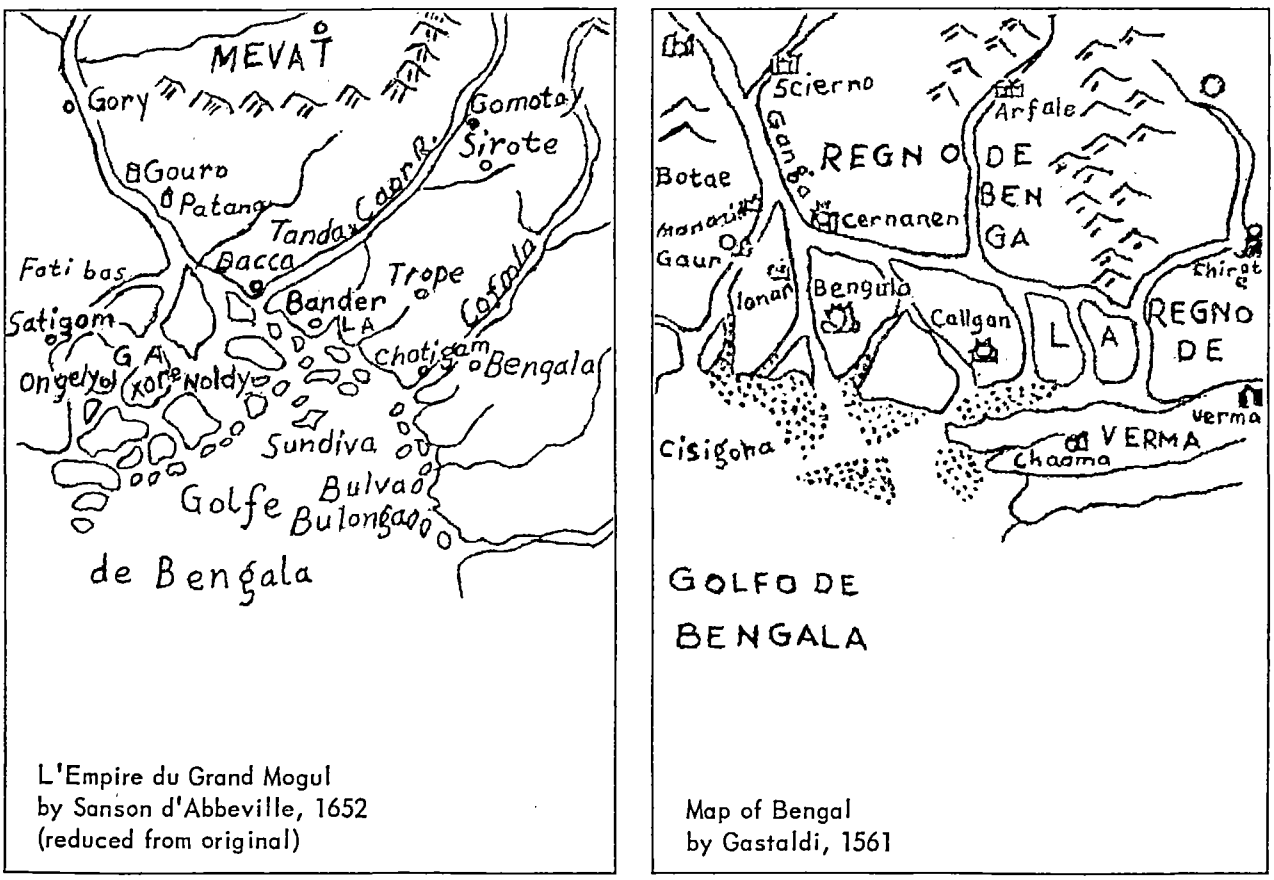


FIG. 1. Ancient maps showing the Ganges delta.

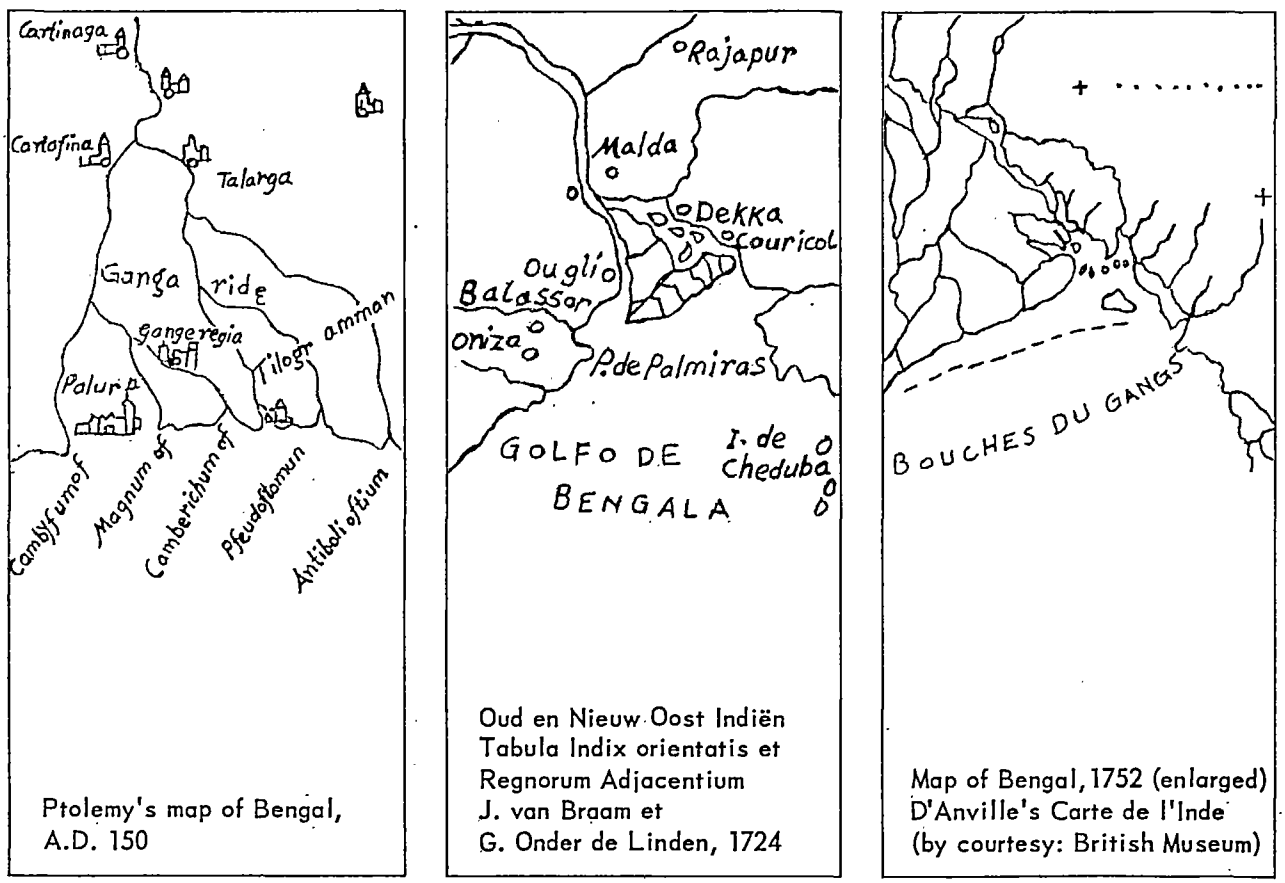
from the accounts of travellers and mariners made from their personal observations, these are considered to be more or less reliable. Sir William Wilcocks, a delta engineer of great renown, had remarked that the Padma channel had always been the main channel of the Ganges, while the Bhagirathi-Hooghly was an excavated channel. However, the unusual growth and development of the western part of the delta, with respect to the eastern part, led everyone, including famous delta engineers, to believe in the idea which is embodied in Spate (1957): "the cardinal factor in the later history of the delta has been the eastward shift of the Ganges water from the western margin, the Bhagirathi, to the present main course, the Padma-Meghna, with such streams as the Ichhamati, Jalangi-Mathabhanga and Gorai representing intermediate positions of the most important channels. Whether this is mainly due to alluviation at the heads of successive main spillways, to tectonic change, to shift in the balance of the delta owing to a change of course elsewhere (e.g., the great shift of the Teesta), or to a secular swing to the east are questions which admit of large and inconclusive debates".

This paper will refute the old idea of the gradual shifting of the Ganges from west to east and, putting an end to that, will establish once for all that the Padma channel has been the main course of the Ganges since the very day of its inception in the deltaic plain.

I have, therefore, endeavoured to disprove the theory of gradual shifting, by three approaches. First, by map comparison from Ptolemy's days to Rennel's maps of 1774; secondly, by the results of laboratory experiments; and, thirdly, by showing that the disproportionate growth and development of the western part of the delta are due to other reasons than the main course of the Ganges passing through this area in ancient times.

As can be gathered from Ptolemy's map (A.D. 150) it is true that during the earlier times of the Christian era the Padma channel has been shown as the prominent one.

On W. Bolt's map, "Carte du Bengale et de Ses Dépendances" (British Museum Map No. PS/3005, 5357(4)), the Padma course is shown as the only channel of the Ganges. It is evident from the same map that the Hooghly distributary was then a very minor channel which, even below the point of confluence of the two heads, the Bhagirathi and the Jellingee, remains an



Ptolemy's map of Bengal, A.D. 150

Oud en Nieuw-Oost Indiën Tabula Indix orientatis et Regnorum Adjacentium J. van Braam et G. Onder de Linden, 1724

Map of Bengal, 1752 (enlarged) D'Anville's Carte de l'Inde (by courtesy: British Museum)

FIG. 2. Ancient maps of Bengal.

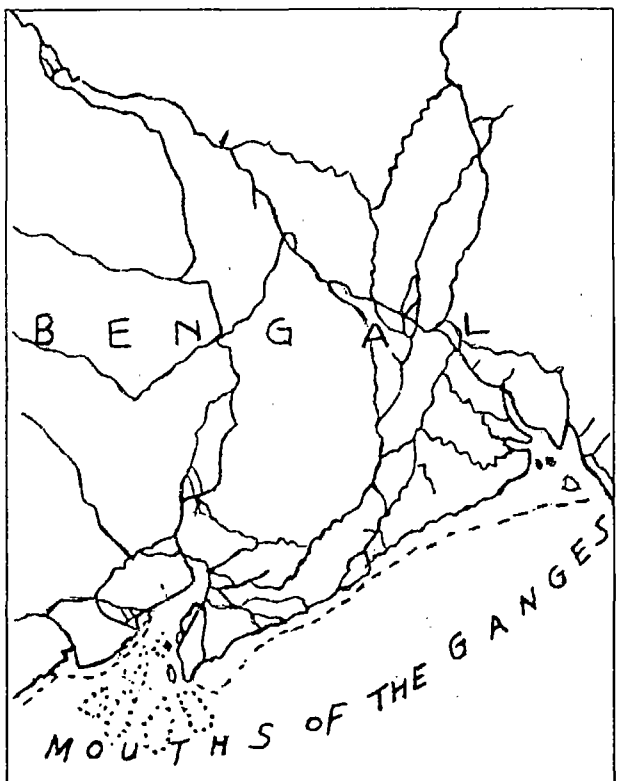
insignificant channel. Moreover, before taking this course the Padma used to flow south-eastward much farther to the north of the alignment which is marked "Les Jeels ou Lacs" on the above-mentioned map. It can be assumed, therefore, that the Bhagirathi-Hooghly channel was never the major course of the Ganges; since the sixteenth century the Padma channel has been the major course.

From the study of another map, "Ragia Werra Cos Bhaar Cos Assam" (British Museum Map No. PS/2792 9. Table 37(57)), it is seen that the Padma channel, which flows south-eastward below Rajmahal, is named the Great River Ganges. Therefore, there is no reason to believe, at least during the Christian era, that the Bhagirathi channel should be considered as having remained the major course of the Ganges.

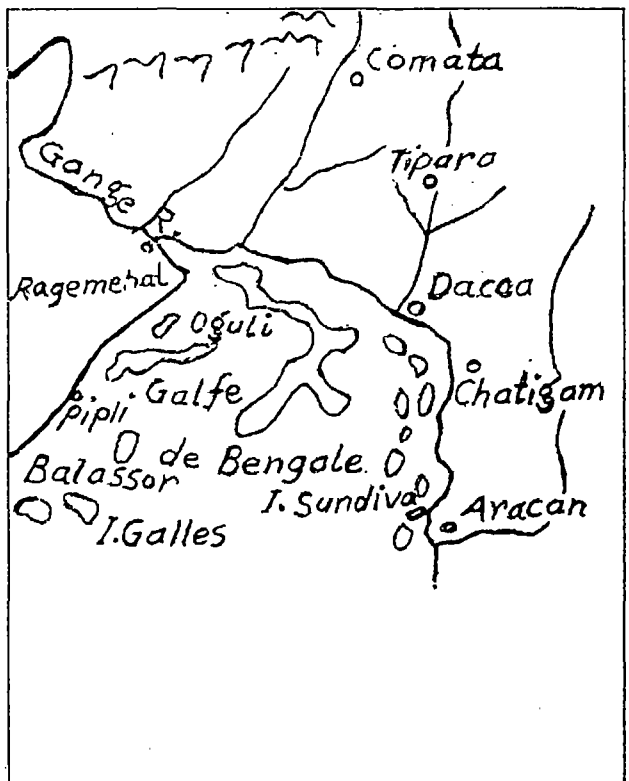
On the map of a famous geographer, Thomas Kitchin, "A New and Accurate Map of Bengal drawn from the Best Authorities" (British Museum Map No. PS/3005, 5357(3)), the bifurcation of the Ganges is shown near Rajmahal; the eastern course, i.e., the Padma channel, is named the Great Ganges and the Bhagirathi-Hooghly channel the Little Ganges.

From the study and comparison of any available maps, it becomes evident that from time immemorial the Padma course has been shown as the major channel fo the Ganges.

Secondly, it may be observed that a natural flow of water, when entering into a plain, loses its gradient and the main course bifurcates into two or more branches. In the case of the Ganges, there is no reason to believe that the main course of the river below Rajmahal should flow through the Bhagirathi-Hooghly channel which, by gradual eastward shifting, forms the Padma channel. An experiment was carried out by the author in the hydraulic laboratory, Cambridge, the physical conditions corresponding as near as possible to those of the natural conditions prevailing here and the result was that the bifurcation of the main course occurred at a point corresponding to that of Rajmahal. From this experimental proof it becomes evident that in the case of the Ganges too, when it first fell into the plain, it bifurcated into at least two channels—the Padma and the Bhagirathi-Hooghly channels. The difference in elevation of the plains of the two channels through which they flow must have been responsible for taking the major flow or discharge through them. And as the eastern region has always been lower in elevation than



Map of Bengal by Thomas Kitchin, 1770
(by courtesy: British Museum)



L'Empire du Grand Mogul
Mer de l'Inde, 1570 (enlarged)

FIG. 2. *(Continued.)*

the western region, the Padma channel must therefore have been the major channel through the ages.

A pertinent argument has always been put forward in favour of advocating that the Bhagirathi-Hooghly channel had been the primary and major channel of the Ganges; it is that the western part of the delta had grown and developed at a disproportionately rapid rate compared to the eastern part. The reasons for this are not far to seek and some of them are explained below.

First, as Auden (1949) has shown, south of the Khasi hills there is a pronounced downwarp filled with Upper and Lower Tertiary sediments and overlain by alluvium. Evans and Compton (1947, p. 221) show that geological correction required for the gravity data amounts, in the Sylhet area, to over 75 milligals, with a positive sign due to the existence of low density sediments. Moreover, the shape of the 75 milligal isogam correction suggests that these Tertiary rocks were folded along north-south axes, in strike continuation with the folds of Tripura and the Chittagong hill tracts (op. cit., p. 228). Since the folding involves also the Upper Tertiary rocks, it is clear that movements subsequent to the elevation of the Shillong plateau took place in the region.

It is not impossible, therefore, that the Miocene uprise of the Shillong plateau also witnessed a similar uprise and connexion in the present Garo Rajmahal gap, and that the gap was breached at a later date at the same time as the Upper Tertiary rocks of Sylhet, Tripura and Chittagong were folded along axes with north-south strikes.

In this connexion the excellent paper by Evans and Crompton on geological factors in gravity determination is referred to as one of great value. They have shown the gravity anomalies after full correction has been made for surface geological formations and isostatic compensation. It is seen that a zone of low negative anomalies running between Burdwan and Bogra terminates abruptly against a region of high positive anomalies related to the Shillong plateau. Indeed, there is a narrow gap of zero anomaly just west of the Garo hills which separates anomaly isogams both of different sign and different geographical alignment. There is reason to believe, therefore, that the sharp discontinuity seen on the surface is also reflected not only in the distribution of masses of Tertiary and post-Tertiary sediments of greatly contrasted thickness, but in the deeper crustal discontinuity striking in a north-west to south-east direction.

The suggestion put forward is that this north-west to south-east zone between the Baxa foothills, the western edge of the Garo hills, Comilla and the Chittagong coast represents a direction along which sag faulting, perhaps accompanied by tear movements with a strong horizontal component, took place in the late Tertiary or Pleistocene, thereby fracturing and breaching the former ridge between the peninsula and the Shillong plateau which may have been elevated during the Miocene.

Moreover, the region below the gap now covered by alluvium must clearly be one of great structural complexity, involving sharp changes in strike and abrupt terminations in structures. Origin and growth of the eastern and western part of the delta must, therefore, have been dependent on this major structural complexity—the eastern part showing a vast inland sea up to the Khasi-Jaintia border within historical times and the presence of an inland sea with crypto-depressions even today.

Secondly the western part of the delta has been developed by sediments carried down by the Ganges, which brings down about 500 million tons of silt annually, whereas the eastern part of the delta is being filled in by the Brahmaputra and the Meghna sediments. The Brahmaputra carries about 900 million tons of silt annually, the contribution by the Meghna being insignificant.

The structural depression on the eastern part of the delta, referred to above, could not therefore be filled in by the enormous quantity of silt and sediment carried by the Brahmaputra and the Meghna together. The entire eastern basin was under a tectonic sea even within the historical period; the relics of this inland sea may be found in the presence of many crypto-depressions in the Sylhet Haors.

Lastly, the kankar, calcareous marl and other mechanical deposits containing carbonate of lime, and the calcareous nodules known as septaria, are so common and widespread in the accumulation of sediments of the western part of the delta, that it is possible that the cementing effects produced by them were responsible to a great extent for the delta-building operations.

Lt. R. Baird Smith (1840) in his paper "On the Structure of the Delta of the Ganges as Exhibited by the Boring Operations in Fort William, A.D. 1836-40", has dealt with this at length, and has also given a comparative analysis of Roman cement and Gazipoor kankar showing that the former contains 73.3 per cent of carbonate of lime and 11.3 per cent of iron oxide whereas the latter contains 72 per cent of carbonate of lime and 7 per cent of iron oxide. He further remarks "from these it will be seen how readily the induration of the kankar may be explained from its close affinity to a substance of which the well-known property is to harden immediately on contact with water".

The bed of calcareous clay, extends from 60 to 65 ft. in depth, gradually loses its colour and continues to a depth of 75 ft., the lower portion of it furnishing nodules of kankar. Again, to a depth of 120 ft. horizontal beds of kankar are occasionally found; ferruginous sand with thin beds of calcareous and arenaceous clay prevail from 208 ft. to 380 ft. " Kankar with minute waterwork fragments of quartz, felspar granite and other indications of debris from primary rocks, are met with in the lower part of this sandy deposit, where also are found those fossil bones which have given to these boring operations so much additional interest and importance." From the building-up of the strata

of the western part of the delta, as is evident from the boring operations, it now becomes apparent that the cementing materials played a very important role from the very beginning. As opposed to this the Brahmaputra or the Meghna silt or sediment contains little or practically no calcareous or any other cementing material. As a result, the building-up of the eastern part of the delta has been dependent only on the accumulation of sediments in the eastern depression. The loose sediments had been affected, carried away over and over again, by subsequent floods and ultimately lost into the sea. Thus the eastern part of the delta has not grown to the extent of the western part.

Without going at length into the discussion of the hydrological factors, the problems of transportation and deposition of sediments, loads of streams and shore profiles, I would like to conclude simply by pointing out the flocculation or coagulation effect on sediments of the western part of the delta. The discharge capacities of the rivers of the western part had always been much lower as compared to those of the eastern part—the alternate tidal action also led to rapid coagulation of the sediments, which had been cemented by the presence of a high percentage of calcium carbonate and bound together. "Particles of colloidal dimension are independent of velocity and are so small that they do not settle in response to gravity and hence remain indefinitely in suspension, or until several unite to make a larger particle. The union is brought about by substances in solution, termed electrolytes, and also by colloids carrying electric charges of opposite sign from those coagulated. . . . Flocculating ability is related to the presence of ions of opposite electric charge, valency, modifying action of ions carrying the same charge as colloids, adsorptions of ions and the concentration of electrolytes in the solution.

"The charge carried by a colloid depends upon the colloid itself and the medium in which it is suspended. Many oxides and hydroxides and colloids of readily oxidizable minerals carry positive charges, whereas minerals not readily oxidized have negative charges. Silica, clay minerals and humus carry negative charges but alumina, ferric oxide and hydroxide, lime, magnesia and hydroxides of chromium, zirconium and others are positively charged. Basic dyes carry positive charges, acid dyes negative charges. Flocculation is hastened by the presence of acids and calcium oxide and hydroxide." (Boswell, 1930.)

Taking this into consideration, flocculation seems to have been occurring on a more rapid scale on the western part than on the eastern part; this being deduced from two points: the nature of the materials and the state of water—comparatively still or turbulent.

The above analyses now convince us that the Padma channel had been through the ages the main channel and the Bhagirathi-Hooghly a mere distributary of the Ganges. The disproportionate growth and development of the western part of the delta is due to reasons other than the accumulation of sediments by it when considered to be the major channel of the Ganges.

Résumé

*Le déplacement progressif d'est en ouest du Gange au cours de la formation du delta (*M.I. Chowdhury*)*

Depuis des temps immémoriaux, on considérait que le bras le plus occidental du Gange, le Bhagirathi-Hooghly était à l'origine le bras principal du fleuve, mais que peu à peu, comme dans le cas d'autres fleuves à diluvium, le lit s'était envasé, le sol s'était exhaussé et le cours principal du fleuve s'était déplacé vers l'est, pour former finalement le bras de Padma, qui est aujourd'hui le bras principal du Gange. L'argument essentiel en faveur de cette théorie était que la progression du delta vers la mer est plus accentuée à l'ouest.

L'auteur de la communication a réfuté la théorie du déplacement progressif du bras occidental et a abordé le problème sous trois apsects : *a*) en comparant toutes les cartes anciennes, depuis Ptolémée (150 après J.-C.) jusqu'à Rennell exclusivement; *b*) en procédant à des expériences de laboratoire; *c*) en constatant que a progression rapide du delta dans sa partie occidentale s'explique par une floculation de sédiments et une cimentation rapide due à une forte teneur en carbonate de calcium ($CaCO_3$) et à la présence d'une faille tectonique le long de la région de Tipperah jusqu'à la côte de Chittagong en passant par l'embouchure du Meghna.

L'étude des cartes anciennes montre que le bras de Padma est le bras principal et celui de Bhagirathi-Hooghly le bras secondaire. Les expériences de laboratoire montrent que, chaque fois qu'un cours d'eau pénètre dans une plaine et que sa pente diminue, il se divise en deux bras au moins. Par conséquent, il n'y a aucune raison de penser que le Gange, en aval de Rajmahal, n'a pas fait de même en entrant dans la plaine.

Il semble assuré, d'après les considérations qui précèdent, que le bras de Padma a toujours été le bras principal du Gange. L'auteur a étudié en détail tous les points ci-dessus, réfutant ainsi la théorie du déplacement progressif du Gange.

Discussion

A. VOLKER. With respect to the statement on page 38, it is not clear why the Brahmaputra carrying 900 million tons of silt annually was unable to fill the depression on the eastern part of the delta whereas the *additional* amount of 500 million by the Ganges is said to have been sufficient.

Historical maps can be interpreted in several ways; it is not permissible to draw conclusions from them on the distribution of flow.

Archaeological evidence points to the fact that the Bhagirathi-Hooghly channel must have been a sacred river with very important temples. The lower course is still called the Ganga-Saga.

The shifting of a river in a delta is not inconsistent with hydraulic laws.

I think that it is worthwhile to examine further Professor Chowdhury's arguments, but that for the time being one cannot say that the theory of the eastward shifting of the Ganges has been put aside once for all. (1) A working hypothesis may be that the Hooghly carried more water formerly than at present and that the Padma existed already in early historical times. (2) What evidence is available that the soils in the east contain less Ca CO_3 than those in the west.

V. N. NAGARAJA. Since the paper was available for reading only at a late hour yesterday, I have not been able to give it the attention it deserves. It deals with a matter of great geomorphological significance and it is obvious that full opportunity should be available for cogitation to enable constructive comments to be made.

I would have appreciated the paper better had I been a geomorphologist myself, but not being one, I shall be content to make some broad remarks which will probably stimulate further research in this respect.

The present knowledge regarding the old course of the Ganges is, to my knowledge, based on archaeological, historical and geotechnical evidence, besides, of course, sketches by travellers. These sources are too important to be ignored. Great changes are known to have taken place around the sixteenth century. Sketches made by travellers can be but a rough guide.

Changes in river courses are not uncommon in history. The Brahmaputra formerly flowed eastward in China before it flowed south to its present course. There are other examples.

I have had a long association with fluvial and tidal hydraulics, and I would say with confidence that the present knowledge does not violate any principle of fluvial hydraulics.

I shall be grateful for an elaboration of the argument regarding carbonate content of the Ganges waters and the consolidation of the western delta. If the influence of the chemical characteristics of the Ganges waters has led to the morphological formation of the western delta, that would not, *prima facie*, lead to the conclusion that the author is assuming.

All in all I would submit that the evidence at present available is not adequate to refute the present knowledge regarding the shifting of the Ganges.

I would very much appreciate the comments of the expert geomorphologists who are present on this absorbing subject.

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Problèmes de sédimentation dans les deltas

L. J. Tison

FORMATION DES DIGUES LATÉRALES

Lorsqu'un fleuve chargé de sédiments débouche dans une mer, la diminution de la vitesse due à l'épanouissement du courant provoque évidemment des dépôts de matériaux solides qui restent sur place si des courants marins, dus à la marée ou non, ne les entraînent pas.

Toutefois, même en l'absence de courants côtiers, les dépôts ne se font pas uniformément dans toutes les directions. Si, dans la partie centrale, les eaux du fleuve continuent plus ou moins leur parcours de façon rectiligne, l'épanouissement dont il a déjà été question donne aux trajectoires qui s'ouvrent latéralement (comme AC par exemple), une allure nécessairement ascendante comme on peut aisément l'établir de la façon suivante (fig. 1).

Quand on considère dans la région de l'étalement une ligne telle que BC, tangente aux normales principales des trajectoires au voisinage de la surface, elle donne lieu à l'équation :

$$z_B + \frac{p_B}{\gamma} = z_C + \frac{p_C}{\gamma} + \frac{1}{g}\int_B^C \frac{v^2}{\rho}\, ds \qquad (1)$$

Une ligne B'C' partant du pied B' de la normale au fond BB' et tracée également tangente aux normales principales du voisinage du fond, donne :

$$z_{B'} + \frac{p_{B'}}{\gamma} = z_{C'} + \frac{p_{C'}}{\gamma} + \frac{1}{g}\int_{B'}^{C'} \frac{v'^2}{\rho}\, ds \qquad (2)$$

Les z sont les cotes par rapport à un plan hozizontal de référence, les p sont les pressions, γ est le poids spécifique de liquide, v et v' sont les vitesses, respectivement à la surface et au fond, et ρ est le rayon de courbure des trajectoires.

D'autre part, par suite de la direction rectiligne des trajectoires centrales AB, la ligne BB', normale au fond comme on l'a dit, est hydrostatique et :

$$z_B + \frac{p_B}{\gamma} = z_{B'} + \frac{p_{B'}}{\gamma} \qquad (3)$$

De la combinaison de ces trois équations on tire :

$$z_C + \frac{p_C}{\gamma} = z_{C'} + \frac{p_{C'}}{\gamma} + \frac{1}{g}\left(\int_{B'}^{C'} \frac{v'^2}{\rho}\, ds - \int_B^C \frac{v^2}{\rho}\, ds\right) \qquad (4)$$

La quantité entre parenthèses est négative, de sorte que la charge $z_{C'} + \frac{p_{C'}}{\gamma}$ au fond est supérieure à celle de la surface. Le mouvement des trajectoires AC sera par conséquent ascendant. Ces trajectoires ascendantes, venant du fond, sont chargées des matérieux les plus volumineux, qui se déposeront sur les bords du courant du fait de l'entrée des courants AC dans une région tranquille.

Sur les bords de la continuation du fleuve en mer se formeront par conséquent des dépôts graveleux et

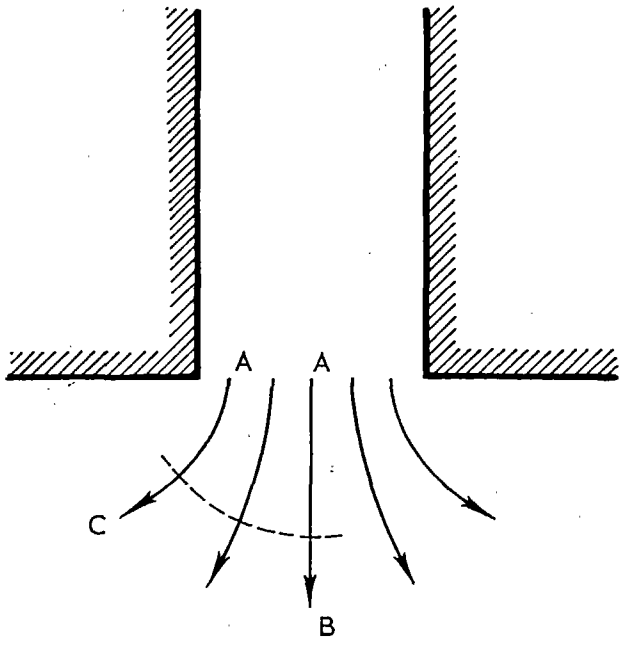

FIG. 1.

sableux qui constitueront des sortes de digues longitudinales, sous-marines au début.

Lors des crues du cours d'eau, ces digues, fortement alimentées, augmenteront de hauteur. Du fait du relèvement du niveau de l'eau sous l'action de la crue, elles resteront cependant sous-marines au fort de la crue, mais émergeront au cours de la décrue pour former de vraies digues qui se couvriront de végétation et se stabiliseront.

Les sédiments plus fins qui sauteront au-dessus des digues iront se déposer dans la zone lentement tourbillonnaire au-delà des digues et même plus loin encore.

Enfin lorsque le courant, usé par les frottements latéraux et les pertes par les mouvements tourbillonnaires, s'amortira complètement, les derniers matériaux solides se déposeront en travers du lit prolongé de la rivière y relevant le fond dans des conditions souvent jugées inacceptables pour la navigation, créant ce qu'on a appelé des barres dont on cherche souvent à éviter les inconvénients par la création de jetées.

De cet exposé résulte que les dépôts en surélévation le long du cours d'eau en mer (digues) seront surtout constitués par des matériaux grossiers, sables et graviers, avec des stratifications entrecroisées non horizontales, mélangées, provenant de la variation des courants ascendants.

Au contraire les dépôts au-delà des digues seront de plus en plus fins en s'en éloignant : limons, argiles, vases. Ces dépôts prendront une cohésion qui croîtra avec le temps sous l'action de leur tassement, de leur consolidation.

On ajoutera encore que les digues latérales dont la formation a été exposée, se prolongent en mer en décroissant d'altitude et en disparaissant finalement sous le niveau de la mer, même basse, pour former un delta sous-marin. Parfois, seule la partie sous-marine du delta existe : c'est le cas lorsque les hauts-fonds entre les divers bras sous-marins ne sont guère alimentés par des apports et sont créés par le fleuve dans des terrains meubles à son embouchure.

PENTES

L'allongement du lit du cours d'eau et la nécessité de disposer d'une pente dans l'allongement du lit conduit à un relèvement du fond du cours d'eau qui se propage d'ailleurs vers l'amont. Ce relèvement n'étant pas instantané, l'équilibre entre la longueur du lit et sa pente n'est en fait jamais réalisé.

Mais ce qui est plus grave, c'est le relèvement mentionné du lit, non seulement dans le delta, mais aussi à l'amont de celui-ci, ce qui conduit à la nécessité de rehausser continuellement les digues du fleuve pour éviter les inondations lors des crues.

On remarquera d'ailleurs que les pentes pourront être d'autant plus faibles que les matériaux amenés par la rivière sont plus fins. Le fond du lit se relève donc moins quand les matériaux transportés sont plus fins, ce qui a comme conséquence que le danger de rupture des digues diminue quand la finesse des matériaux transportés augmente.

Une autre considération renforce d'ailleurs cette conclusion. Lorsque les matériaux transportés sont fins, les digues latérales bien que constituées des éléments les plus grossiers, comme on l'a dit plus haut, sont aussi en matériaux assez fins qui, par la cohésion propre à ces matériaux, donnent aux digues une résistance plus grande.

FORMATION DE MULTIPLES BRAS

Très souvent le fleuve se jette en mer par un véritable éventail (disposition en patte d'oie), avec de multiples bras : nous ne devons pas multiplier les exemples de semblables dispositions.

La formation de chacun de ces bras est due à la rupture — lors de hautes eaux — d'une des digues naturelles dont il a été question ci-dessus, digues qu'on devine assez fragiles. On a parfois écrit que, lors de semblable rupture, l'ancien bras a tendance à s'envaser et à être finalement abandonné après un temps plus ou moins long.

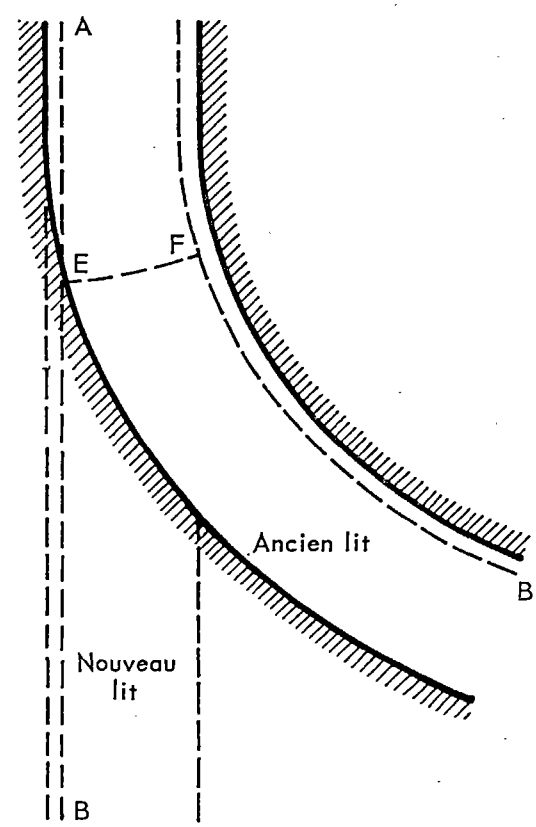

FIG. 2.

Ce point est très discutable. La rupture peut se faire à un angle de l'ancien lit : ces points sont en effet en général des endroits de moindre résistance, du fait que la rive concave est minée par les érosions du fleuve. Dans ce cas, le nouveau lit devient la continuation rectiligne du lit en amont de la rupture.

Par une démonstration analogue à celle qui a été faite en début d'article en envisageant des trajectoires AB et CD (fig. 2) et des lignes principales EF à la surface et E′ F′, au fond, on établirait que les trajectoires CFD se dirigeant vers l'ancien lit sont nécessairement ascendantes. Venant du voisinage du fond, ces trajectoires entraînent vers l'ancien lit la plus grande partie du débit solide alors que le débit liquide antérieur y est considérablement réduit. Une tendance marquée aux dépôts par sursaturation s'établit donc dans l'ancien bras, qui par conséquent tend bien à se combler.

On remarquera que si la rupture se fait encore à un coude (fig. 3), mais sans que le nouveau bras réalise un écoulement rectiligne, il se réalise plutôt une disposition symétrique qui donne évidemment lieu à un partage balancé des débits solides sans que l'un des deux bras ait tendance à se combler.

Enfin si la rupture se produit dans un ancien lit rectiligne (fig. 4), les considérations exposées ci-dessus montrent que la majeure partie du débit solide passe par le nouveau bras. Si ce nouveau bras atteint la mer plus rapidement que l'ancien, il est possible que le supplément de pente dont le nouveau bras dispose ainsi lui donne des vitesses lui permettant d'évacuer le débit solide qu'il reçoit. Mais avec le temps, le nouveau bras s'allongera et sa pente se réduira, diminuant ainsi sa capacité d'évacuation solide, ce qui entraînera dans ce bras une tendance à la sédimentation et au comblement.

Le delta du Mississippi permet une application des considérations théoriques ci-dessus. La figure 5 donne une idée de ses principaux éléments.

Du bras principal, se détache à environ 300 milles de son embouchure, un bras secondaire mais important, l'Atchafalaya River (qui s'appelle Old River en quittant le fleuve); ce bras reçoit divers affluents et se jette dans le golfe de Mexique à un peu plus de 100 milles de son point de départ. En 1929, ce bras évacuait de 14 à 15 % du débit total du Mississippi, mais en 1951, cette proportion était montée à 24-26 % .Un rapport de cette époque estimait que sans contrôle artificiel l'Atchafalaya finirait par dériver tout le débit du Mississippi.

L'Old River (début de l'Atchafalaya) se détache quasi perpendiculairement du bras principal. En vertu des considérations théoriques émises ci-dessus, l'Atchafalaya doit dériver une bonne partie du débit solide entraîné sur le fond. C'est ce qui se passe en effet, bien que cette diversion soit quelque peu réduite par le fait que la dérivation se détache d'une rive concave, alors que le cheminement des matériaux se fait sur le fond de la rive convexe. D'autre part, le Mississippi charrie très peu de matériaux grossiers, mais transporte surtout des matériaux très fins en suspension. L'influence de la courbure sur ceux-ci est évidemment moins prononcée que sur les matériaux charriés : cependant, en 1951, l'Atchafalaya entraînait de 28 à 31 % des matières en

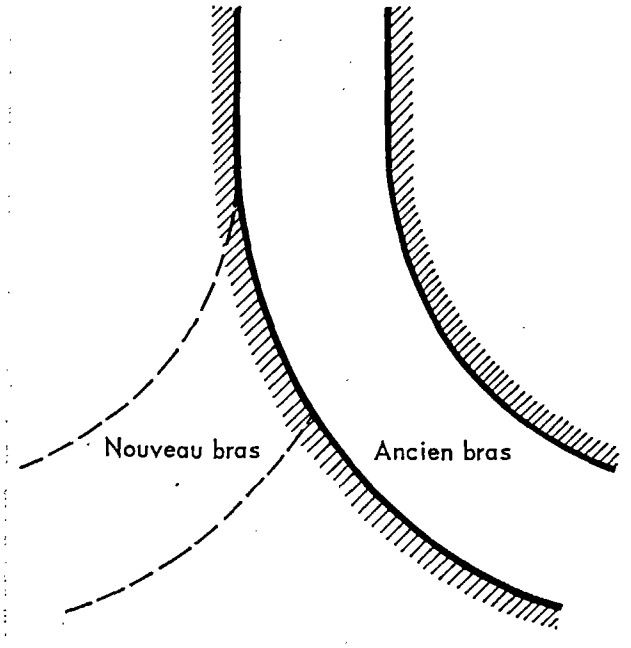

Fig. 3.

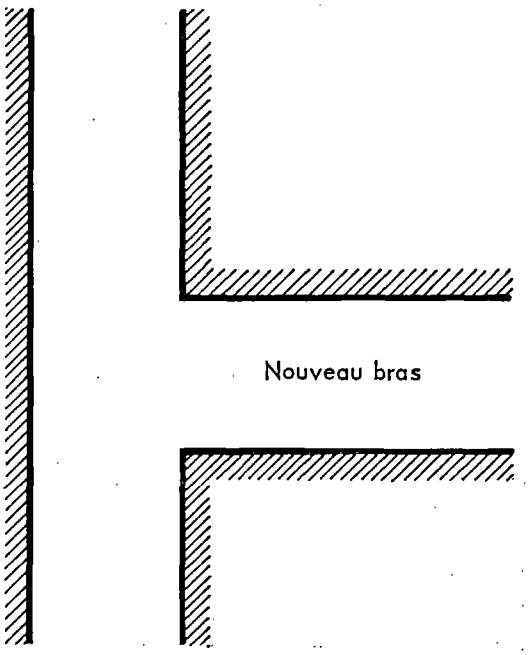

Fig. 4.

suspension, alors qu'elle ne dérivait, comme on l'a vu, que 24-26 % du débit liquide.

Si on considère maintenant le bras principal du Mississippi, on voit qu'il se termine par trois branches principales : celle du sud-ouest, celle du sud et la Pass a Loutre. Une première division se fait entre la Pass a Loutre et un autre bras qui donnera lui-même les deux autres passes. Par rapport à l'axe du lit d'amenée, la bifurcation au départ de la Pass a Loutre est assez grossièrement symétrique, la Pass a Loutre s'écartant peut-être un peu plus de cet alignement. Il faut donc s'attendre à un partage des sédiments sensiblement proportionnel aux débits liquides (45 % vers la Pass a Loutre). Il semble bien que c'est ce qui se produit (fig. 6). A l'aval de la bifurcation dont il vient d'être question, s'en produit une seconde dans laquelle chacune des deux branches nouvelles conserve sensiblement, sur une certaine longueur, l'alignement de la branche dont elle est issue. Ce parallélisme est encore accentué par l'ouvrage construit entre ces deux bras, à leur séparation. La conséquence en est que la courbure ne joue aucun rôle sur la répartition des matériaux qui vont aussi bien vers le bras du sud-ouest que vers le bras du sud. Les débits solides doivent s'y répartir à peu près sous la seule action des débits, et les profondeurs des deux bras ont tendance à se maintenir avec cependant un avantage pour la passe du sud-ouest, qui, du fait de sa largeur, reçoit la grosse part du débit liquide et où, en conséquence, les vitesses sont moins réduites par le frottement. (La passe du sud-ouest reçoit en effet 40 % du débit total du Mississippi en hautes eaux.)

Quant il est question des profondeurs, il faut cependant remarquer que la formation de dépôts sous forme de barres au débouché en mer de chacun des bras réduit fortement la hauteur d'eau. Les trois débouchés ne se comportent pas d'ailleurs de même façon. Un courant littoral, grossièrement dirigé d'est en ouest, rejette en effet vers la droite de l'embouchure les sédiments qui débouchent des passes sud et sud-ouest, alors que ce courant est sans action sur les sédiments de la Pass a Loutre qui est sensiblement dans la direction du courant littoral. A l'embouchure de cette passe, les sédiments se déposent donc assez uniformément en éventail, y réduisant la profondeur à quelque 10 pieds, tandis qu'aux deux autres embouchures, le courant côtier, aidé par l'action de jetées et de quelques dragages, permet d'entretenir des profondeurs de l'ordre de 35 pieds au débouché de la passe sud-ouest et de 30 pieds pour l'autre.

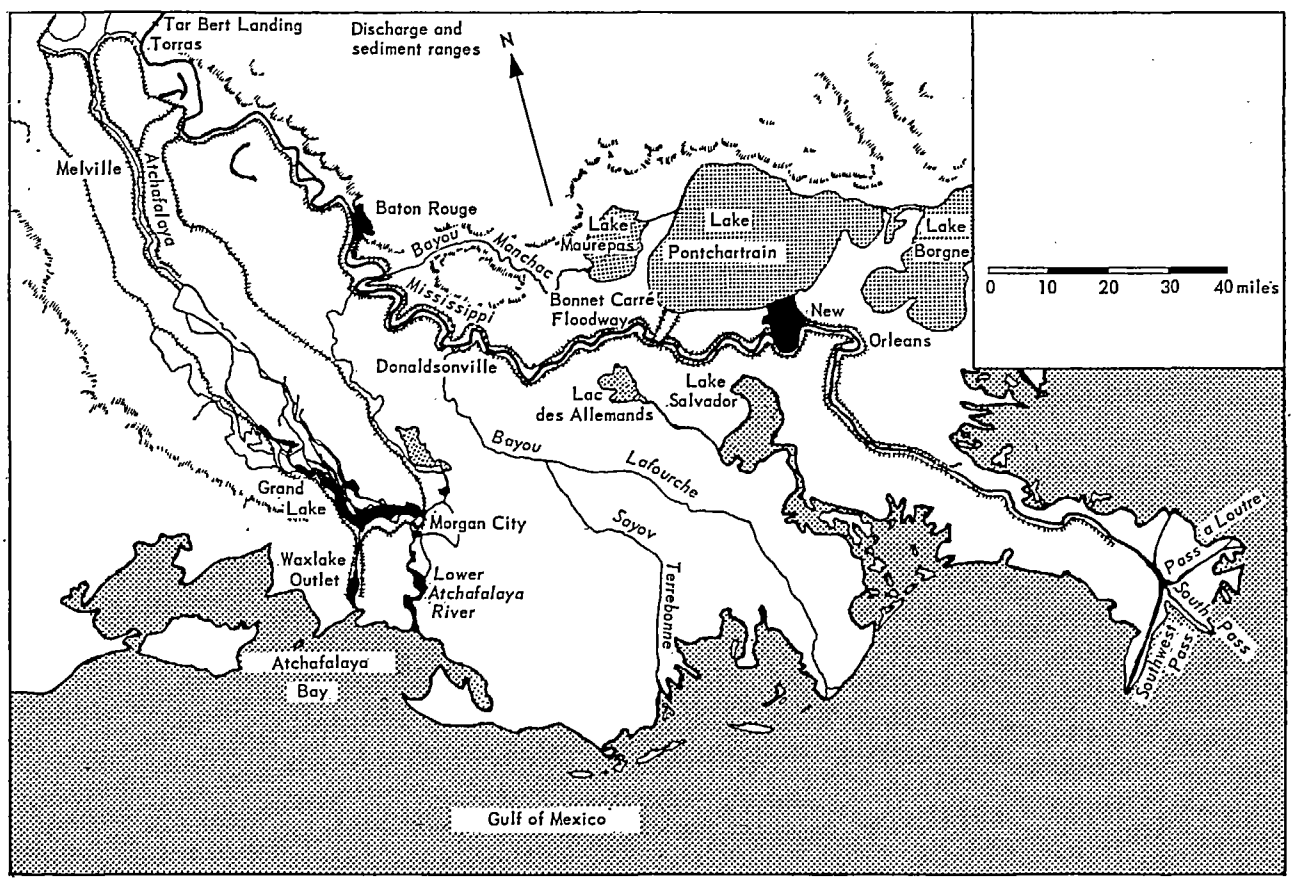

FIG. 5. Atchafalaya et Mississippi inférieur.

Mais à côté de ces branches principales du delta du Mississippi, il en existe d'autres qui sont loin d'atteindre l'importance des trois branches mentionnées. Toutes ces autres branches quittent le fleuve en ces embranchements quasi perpendiculairement à la direction générale. Leur disposition est donc telle qu'elles évacuent, par rapport à leur débit liquide, une plus forte proportion de sédiments. En dépit du fait que ces branches sont plus courtes, elles n'arrivent cependant pas à prendre de l'importance : certaines ont été barrées.

Des considérations du même genre pourraient être faites pour le delta du Pô, comme le montre l'étude présentée au Congrès de navigation de Rome (Visentini *et al.*, 1953). On y voit en effet que dans ce cas aussi, « le fleuve tend à donner le plus d'importance à l'embouchure dont le parcours est plus court que les autres » (fig. 7).

Comme on le montrera plus loin, cette règle n'est d'ailleurs pas absolue lorsque interviennent d'autres facteurs, comme la marée par exemple.

Peut-être aussi pourrait-on tirer de cette étude du Pô des confirmations de l'influence de la courbure, comme on l'a exposé ci-dessus : il semble en effet que certains bras se séparant sous un angle assez vif ont perdu de leur importance, du fait de l'attrait qu'ils exerçaient sur les matériaux solides qui d'une part allongent continuellement le bras qui les transporte et d'autre part finissent par augmenter la résistance ce ce bras par les dépôts auxquels ils donnent lieu. Ces actions conduisent à la sédimentation de ces bras.

Le phénomène tel qu'il vient d'être exposé est celui qui se produirait pour un fleuve débouchant dans un lac d'eau douce, sans courants littoraux.

Pour les fleuves débouchant en mer, le phénomène est beaucoup plus complexe, sous l'action de multiples influences parmi lesquelles on peut citer les actions réciproques de l'eau douce et de l'eau salée, l'intervention de la marée et de la houle, ainsi que des courants qu'elles peuvent provoquer, l'influence du vent, etc.

ACTIONS RÉCIPROQUES DES EAUX DOUCES ET SALÉES

Quand l'eau douce du fleuve arrive au contact de l'eau salée marine, quatre cas sont à priori possibles :

1. Les eaux douces coulent sur les eaux salées plus denses sans qu'il y ait mélange à l'interface.
2. L'écoulement en question se fait avec mélange peu accentué à l'interface.

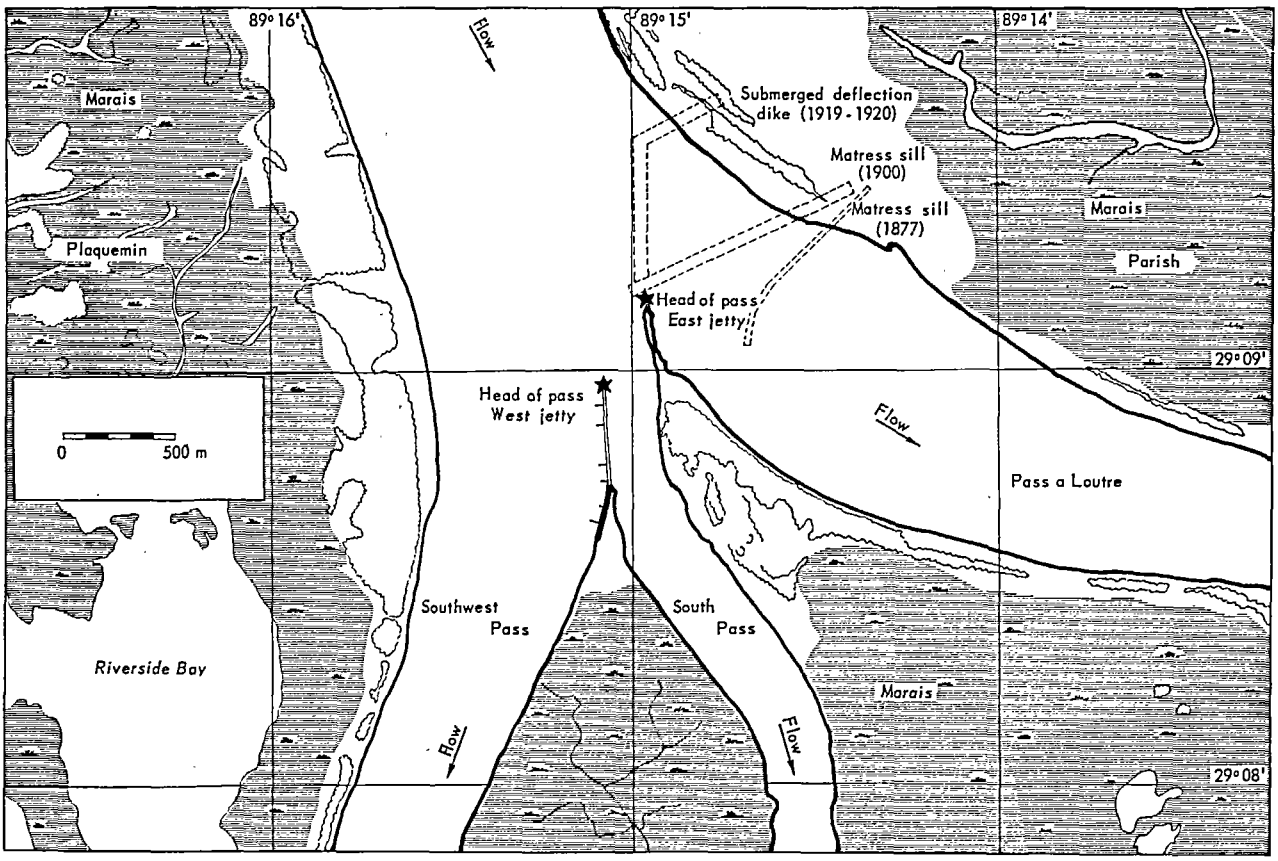

FIG. 6. Mississippi.

3. Cet écoulement se fait avec mélange plus accentué à l'interface, conduisant à une stratification horizontale des couches dont les densités décroissent plus ou moins continuement vers le haut.
4. L'écoulement se fait avec un tel mélange que les isohalines se redressent, devenant même quasi verticales.

Ces questions ont été étudiées par de nombreux auteurs (on trouvera notamment une liste d'études se rapportant à ces questions dans : L. Tison, 1955).

En fait, le premier cas ne se rencontre pas dans les cours d'eau naturels, mais le cas de deux liquides non miscibles a servi de base à l'étude de tous ces problèmes.

Les recherches ont notamment porté sur la question de l'instabilité de l'interface, instabilité résultant de la naissance d'ondes qui dans certaines conditions se déplacent à l'interface avec des amplitudes croissantes conduisant au déferlement et par suite au mélange. Des critères ont été établis dans lesquels interviennent le nombre de Reynolds et un nombre modifié de Froude. Des études théoriques et de laboratoire ont donné certaines solutions à ces problèmes, mais leur exposé nous entraînerait trop loin (L. Tison, 1955).

Si on ne rencontre que les trois derniers cas cités ci-dessus dans les estuaires, il faut cependant ajouter que les critères dont il vient d'être question jouent cependant un rôle important lorsqu'on a recours à des modèles réduits, la similitude exigeant naturellement que le passage de l'eau salée à l'eau douce se produise de la même façon dans le modèle et dans le prototype.

On se limitera cependant à l'examen des trois derniers cas envisagés.

Encore faut-il ajouter que pour les questions qui nous intéressent ici, les deux catégories de problèmes compris sous les points 2 et 3 ci-dessus peuvent être étudiés ensemble. On se rend compte en effet que des limites bien nettes n'existent pas entre les diverses catégories présentées et qu'on rencontre tous les cas établissant un passage graduel de l'un à l'autre des groupes, parfois sur une même rivière par suite de variations locales de certaines influences.

Pour les rivières de la catégorie 3, la variation de la salinité du fond à la surface se présente presque toujours avec une zone de variation rapide à une certaine profondeur, suivant ce que montre la figure 9. Pour les rivières du groupe 3, tout se passe donc sensiblement comme dans les rivières du groupe 2, l'écoulement supérieur d'eau douce de ce dernier groupe étant remplacé par le mouvement d'un liquide graduellement moins salé en se rapprochant de la surface, tandis qu'une zone peu épaisse de variation rapide de la salinité remplace la région de l'interface de la catégorie 2.

On étudiera donc d'abord les rivières de cette dernière catégorie, mais les conclusions générales pourront être étendues à celles du groupe 3.

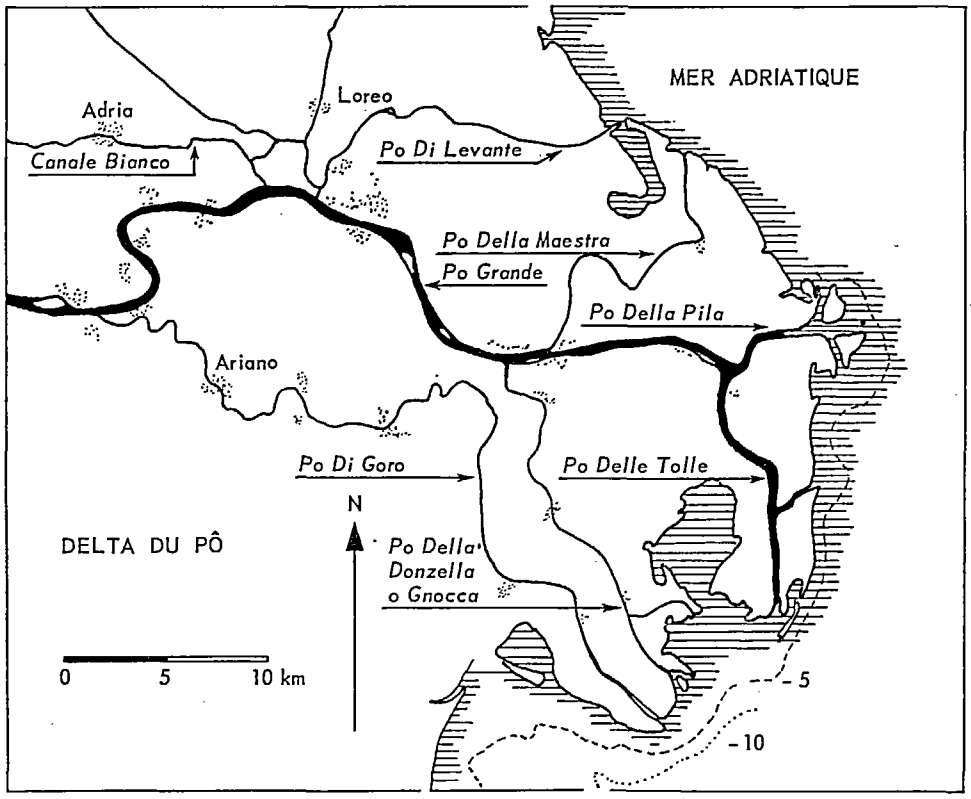

FIG. 7. Delta du Pô.

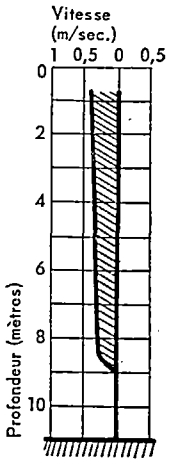

FIG. 8. Répartition des vitesses dans l'embouchure du Rhône (d'après Danel, Congrès de navigation, Rome, 1953).

Rivières avec mélange peu accentué à l'interface

Ce cas se produit particulièrement dans les cours inférieurs de rivières débouchant dans des mers sans marée ou avec faible marée. On le rencontre sur les cours d'eau aboutissant à la Méditerranée (le Rhône par exemple), sur ceux du golfe du Mexique (Mississippi, Calcassieu River etc.) (fig. 8).

Si les circonstances d'aval et le débit d'amont restaient constants, la forme de l'interface pourrait être déterminée en intégrant les équations du mouvement et de continuité de chacune des couches; ces équations contiennent cependant malheureusement le coefficient de frottement à l'interface, coefficient bien difficile à déterminer. D'autre part, le débit d'amont tout comme les circonstances d'aval (par exemple le niveau d'aval soumis à la marée) sont essentiellement variables. L'eau salée provenant de l'Océan se propage sur une certaine distance vers l'amont en formant ce qu'on a appelé une « langue » (*wedge*) salée sur le fond. La distance sur laquelle s'établit cette langue varie avec l'importance du débit d'amont, avec la marée et les autres conditions d'aval, vent, courants, etc.

Les vitesses s'annulent au voisinage de la zone de contact des deux eaux; dans la langue salée, elles sont dirigées vers l'amont pour maintenir cette langue salée dont la surface est usée par l'écoulement supérieur de l'eau douce vers l'aval et aussi pour gonfler ce coin lors de son extension vers l'amont sous l'action, par exemple, de la marée montante ou d'une réduction du débit d'amont. Ce coin fluctue donc continuellement.

L'existence de ce coin salé joue un rôle de première importance dans la sédimentation. Tout d'abord, la salinité de l'eau produit une floculation de substances en suspension et dissoutes. Mais il y a plus : l'existence d'une interface, dans la région de laquelle les vitesses s'annulent ou deviennent très faibles, crée une zone des plus propices pour la sédimentation, déjà facilitée par la production des étales de flot et de jusant. Les matériaux arrivant dans la zone de l'interface et dans le coin où les vitesses sont généralement réduites se déposeront donc aisément.

Le phénomène est très nettement marqué sur le Mississippi aux époques de hautes eaux (fig. 9). Le coin salé est alors refoulé vers l'embouchure, et sur la passe du sud-ouest il se trouve entre les milles 18 et 19, alors que l'extrémité des jetées se trouve vers le mille 20. On constate dans ces conditions la production d'atterrissements vers l'extrémité des jetées comme le montre la figure 10 empruntée à Chester A. Peyronnin Jr. (1961). Cet auteur a d'ailleurs pu établir de façon très précise, par l'analyse des sédiments, la production des dépôts dans la zone de l'interface.

A remarquer toutefois qu'aux basses eaux, quand le coin salé remonte jusqu'à proximité de Head of Passes et même en amont, aucun dépôt notable ne se produit. Le mouvement des sédiments aux faibles vitesses correspondant à ces basses eaux est en effet très réduit.

Il y a d'ailleurs dans les estuaires une autre région qui est également propice à la sédimentation : c'est l'extrémité amont du domaine fluvio-maritime de la rivière, où la sédimentation des matériaux les plus grossiers est facilitée par la production des étales.

D'un autre côté, le fait que le courant dans le coin salé est dirigé vers l'amont donne lieu dans de nombreux cas à des remontées de sables et de matériaux marins sur le fond de la rivière. Cela est particulièrement le cas lorsque des courants littoraux passent à l'embouchure des fleuves à marée et assurent à cet endroit une alimentation continue de l'eau marine en matériaux solides. Des cas de cette espèce seront plutôt étudiés lorsqu'il sera question de l'influence des courants littoraux.

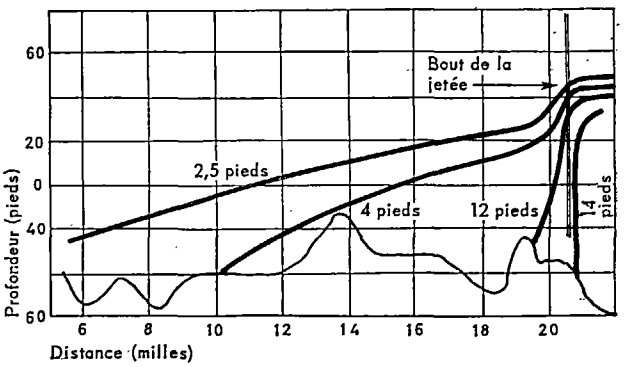

FIG. 9.

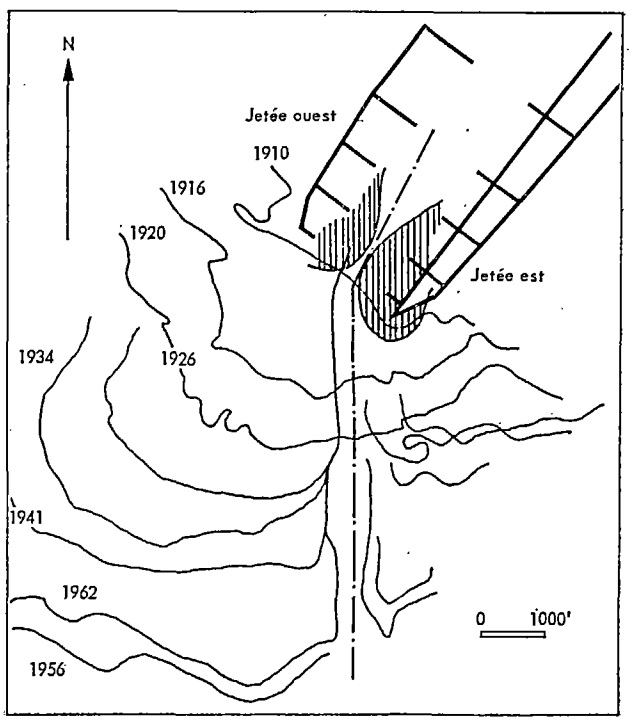

FIG. 10.

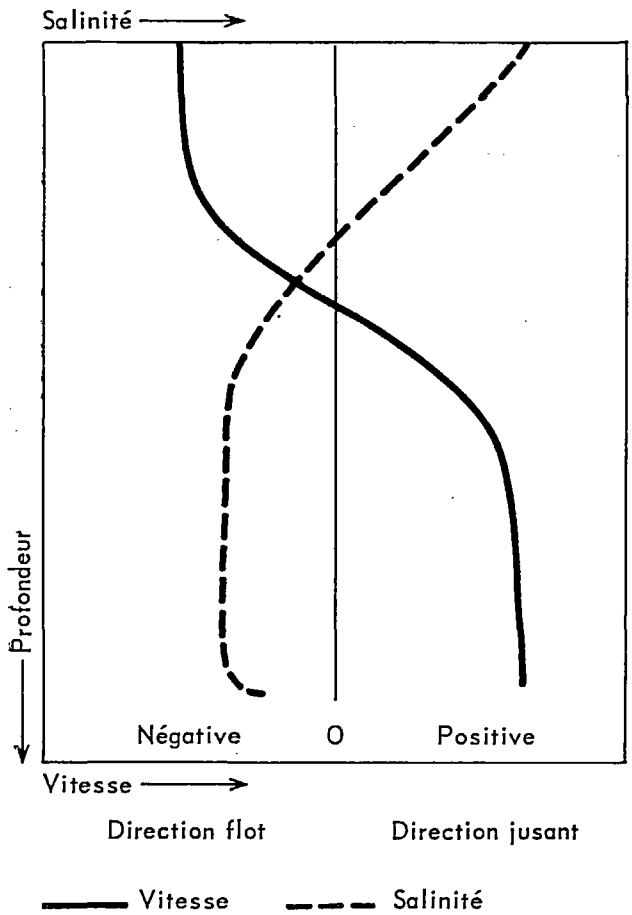

FIG. 11.

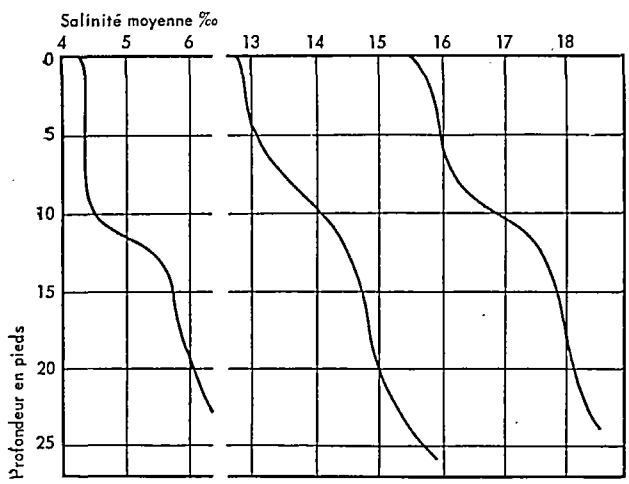

FIG. 12. Courbes de répartition de la salinité dans trois sections de la Janus (d'après Pritchard).

Rivières avec mélange plus accentué, conduisant à une stratification horizontale de couches de densités décroissant vers le haut (fig. 11)

Comme on l'a vu plus haut, leur étude ne diffère guère de celle des rivières dont il vient d'être question, du fait de l'existence d'une zone à forte variation de densité et de vitesses quasi nulles (fig. 12). C'est le cas d'une bonne partie de rivières débouchant dans l'Atlantique là où les marées deviennent plus importantes. Certaines d'entre elles appartiennent cependant à la catégorie 4.

D'autre part, même si la marée a pour effet d'inverser le sens des courants pendant le flot et le jusant sur toute la hauteur d'une section transversale, on constate cependant que dans la partie supérieure de la section, le débit net est dirigé vers l'aval, tandis qu'il s'écoule vers l'amont dans la partie inférieure. Ceci conduit à ce que, en fait, l'estuaire se comporte encore comme constitué de deux couches qui ne sont cependant pas homogènes au point de vue de la salinité. Cette structure se reflète d'ailleurs sur la forme des courbes de salinité (fig. 12), qui présentent un point d'inflexion vers la mi-hauteur. Le frottement de ces deux couches l'une sur l'autre provoque un transfert d'eau salée à la couche supérieure (fig. 13).

La direction et l'intensité du vent, en accumulant les eaux de surface moins salines soit vers l'aval, soit vers l'amont, soit encore latéralement, provoquent évidemment des modifications de l'équilibre. Cette considération s'applique d'ailleurs aussi à la section précédente.

Pritchard a aussi observé que sous l'influence de la rotation de la terre, les concentrations salines dans une section droite sont plus élevées vers la rive gauche que vers la rive droite.

On sait en effet que la rotation de la terre donne naissance à une force dite « de Coriolis », perpendiculaire à la vitesse et dirigée vers la droite de l'écoulement dans l'hémisphère nord. Pour les estuaires envisagés par Pritchard avec le type de circulation de la figure 14 (Chesapeake Bay), l'eau douce de surface s'écoulant vers l'aval est donc poussée vers la rive droite, alors que l'eau salée du fond dirigée vers l'amont est déviée vers la rive gauche, les deux actions se complétant pour obtenir le schéma de la figure 14. Cette action peut avoir une influence sur la sédimentation; l'interface prenant également la forme distordue des lignes isohalines de cette figure, il se produira, toutes autres choses égales, une sédimentation s'étendant plus à l'amont sur la rive gauche que sur la droite.

Pour se rendre compte de l'influence de la salinité dans la partie maritime de ces fleuves à marée, on pourra comparer les deux figures 15 : la supérieure donne les vitesses de flot et de jusant, à la surface et au fond, dans un modèle à marée utilisant l'eau douce, tandis que l'inférieure donne les mêmes variations quand l'eau de l'océan, dans le modèle, est de l'eau salée. On y remar-

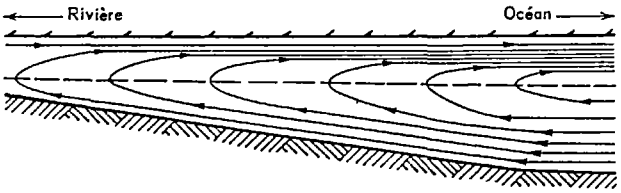

FIG. 13. Représentation schématique des lignes de courant dans un estuaire type de la Chesapeake Bay (d'après Pritchard).

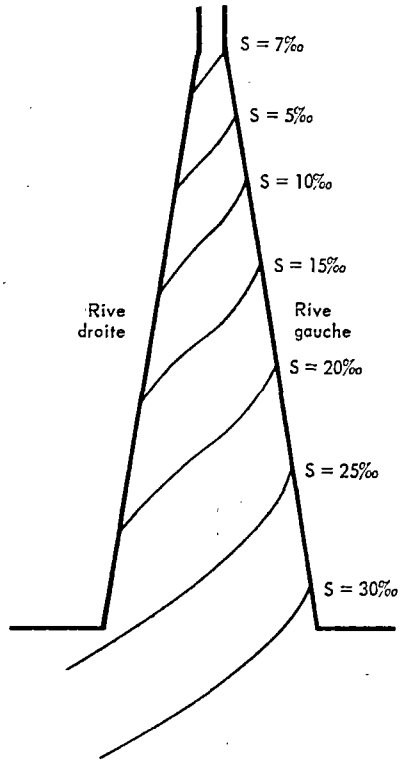

FIG. 14. Influence de la rotation de la terre sur les isohalines d'un estuaire (d'après Pritchard).

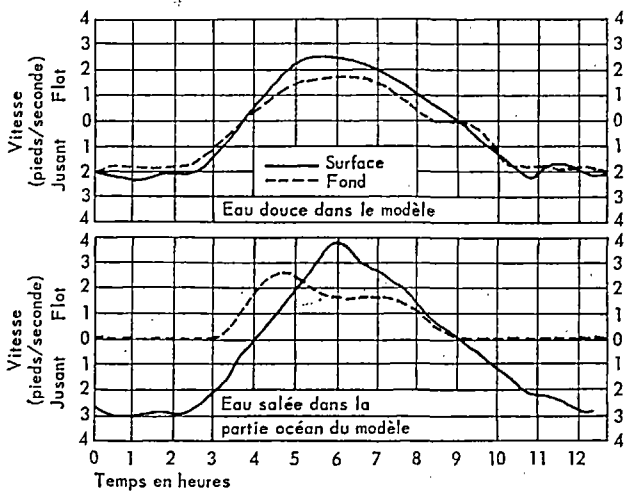

FIG. 15. Variation de la vitesse dans une section de la Savannah (d'après Simmons).

quera surtout que, dans ce dernier cas, l'eau du fond n'est jamais dirigée vers l'aval. Dans une telle rivière, seule une partie des substances en suspension arrivera à la mer, mais aucune évacuation de sédiments de fond ne sera possible.

Le problème suivant permet de se rendre compte de l'influence exercée par le mode de répartition de la salinité sur la sédimentation. Il s'agit de la rivière Hudson entre les États de New York et de New Jersey. La figure 16 montre les régions de sédimentation, dont les principales sont celles marquées shoal 5 et shoal 6, à l'aval du pont George Washington. L'explication de cette répartition donnée par C. M. Duke (1961) est la suivante. Le courant salé de fond, dirigé surtout vers l'amont, y entraîne non seulement les matériaux primitivement charriés, mais aussi et surtout les substances originellement en suspension et qui ont atteint le fond après floculation du fait de leur contact avec l'eau salée. Ce courant de flot, de fond, se localise le long de la rive gauche, aux grandes profondeurs et il entraîne les matériaux dont il vient d'être question jusqu'à l'aval du pont Washington. Le rétrécissement local de la rivière en cet endroit provoque une agitation qui remet

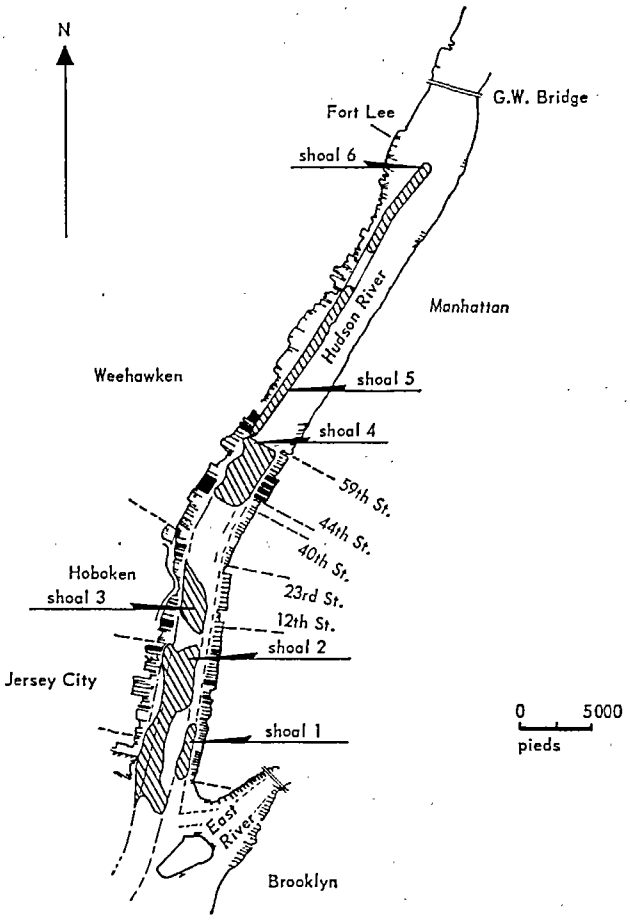

FIG. 16. (d'après C.M. Duke).

une bonne partie des sédiments temporairement et localement en suspension. Ils repassent dans la zone supérieure, aux eaux plus douces, dirigées vers l'aval, et reviennent dans la zone plus calme où ils se déposent, d'abord à l'aval du pont (shoals 6 et 5) et ensuite plus à l'aval.

Ajoutons qu'à notre avis la localisation de courants salés de flot vers la rive gauche ainsi que les grandes profondeurs qu'on y trouve s'expliquent par la force de Coriolis, qui peut justifier également la localisation des courants de surface, d'èbe, et par conséquent l'existence des dépôts, le long de la rive droite.

On trouve ici un bel exemple d'un estuaire du type 3 dans sa partie aval et que le rétrécissement du pont transforme en estuaire du type 4.

Rivières avec mélange si accentué que les isohalines se redressent et peuvent même se présenter verticalement

Il a déjà été dit que l'Europe occidentale comptait d'assez nombreux estuaires de ce type (Escaut, Elbe, etc.), la transition avec le type précédent étant d'ailleurs assurée de façon graduelle par de nombreux estuaires. La variation de la salinité devient alors une fonction de la distance à partir de l'extrémité amont du domaine maritime.

Arons et Stommel (1951) ont établi une théorie permettant de trouver la variation de la salinité avec x en se basant sur l'équation de base de la diffusion. Ils arrivent à une expression :

$$\frac{s}{\sigma} = e^{F(1-1/\lambda)}$$

$\frac{s}{\sigma}$ est la salinité relative (par rapport à la salinité σ à l'embouchure) dans une section x,

$$F \text{ vaut } \frac{v H^2}{2 B \zeta_0^2 \omega L} \quad \text{et} \quad \lambda = \frac{x}{L}$$

H est la profondeur de la partie maritime du lit, ζ_0 est la demi-amplitude de la marée, ω vaut $\frac{2\pi}{T}$, L est la longueur de la partie maritime et v est la vitesse que donnerait le débit d'amont dans la section maritime supposée de profondeur et de largeur constantes par les auteurs. B est un coefficient sans dimension. L'origine de x est l'extrémité amont du domaine maritime du fleuve.

Appliquée à l'Escaut, l'Elbe, le Weser, la variation ainsi obtenue de $\frac{s}{\sigma}$ ne correspond pas tout à fait à la réalité. Au contraire, la concordance devient quasi parfaite si on pose, $v = v_0 (1 - \alpha\lambda)$, comme nous l'avons proposé avec α coefficient constant inférieur a 1, cette expression de v exprimant que la section de la partie maritime croît linéairement avec x. La figure 17 donne ces variations de $\frac{s}{\sigma}$ avec x.

Ces courbes permettent d'avoir une idée de l'emplacement des sections où la floculation sera particulièrement intense. Cette floculation semble en effet être affectée par le rapport de l'eau salée à l'eau douce (10 à 15 % d'après Duke), les propriétés réactives des particules intervenant (surtout leur finesse, < 0,002 mm) ainsi que le pH (< 7) et la température de l'eau. La proportion indiquée pour l'eau saline correspond pour l'Escaut à $\lambda = 0{,}5$ à 0,55, tandis que pour l'Elbe, avec son fort débit d'amont, $\lambda = 0{,}75$. Ceci correspond sensiblement à l'aval immédiat d'Anvers pour l'Escaut. A remarquer cependant que cet emplacement dépend du débit d'amont. Pour le débit d'été, cette section est reportée vers l'amont : or, du fait de l'influence de la température sur la floculation, la situation d'été sera surtout à prendre en considération.

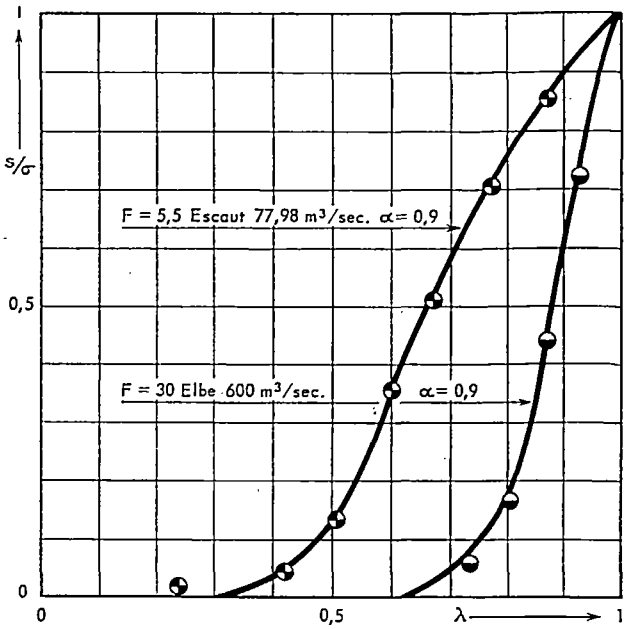

FIG. 17. Variations de la salinité relative en fonction de la longueur relative dans un estuaire à section s'élargissant vers l'embouchure.

Van Veen a signalé que l'ouverture de nouveaux ports sur la Nieuwe Waterweg y avait facilité l'intrusion de la salinité. Il en est de même de tout ce qui peut faciliter le mélange et notamment de tous les obstacles, prises et remises d'eau, etc., qui créent des courants secondaires plongeants ou ascendants, favorables au mélange.

Un phénomène assez curieux d'accroissement de sédimentation avec le temps a été constaté à l'extrémité amont du bassin maritime de l'Escaut et particulièrement sur un de ses affluents, la Durme. Cette rivière a pu être maintenue aisément navigable sans grands travaux de dragage jusqu'en 1914. Depuis lors, le lit de la rivière se comble si rapidement que la navigation a dû être interrompue après plusieurs dragages considérables dont les effets ne duraient guère. On a cru mettre en cause la diminution du débit d'amont du

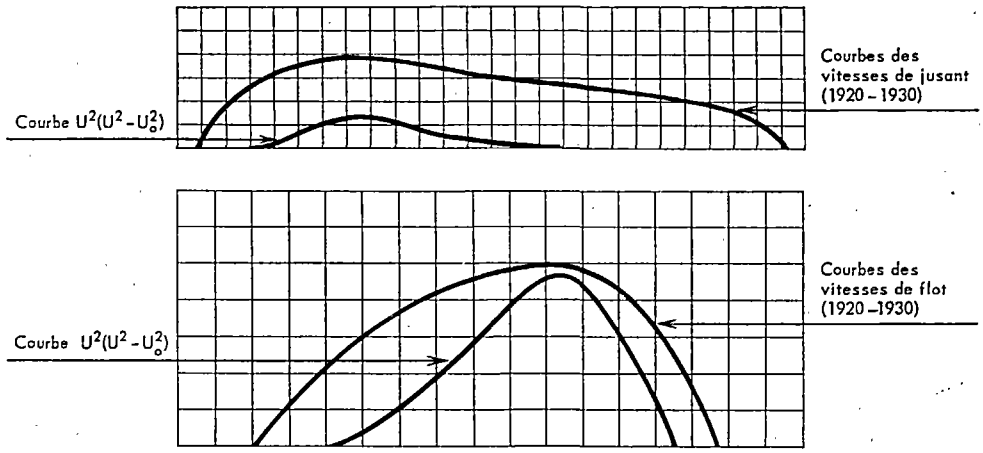

FIG. 18. Station de Waasmunster (1920-1930).

fait des détournements vers d'autres bassins d'une partie importante des eaux alimentant autrefois la rivière. Toutefois, ces détournements sont bien antérieurs à la date indiquée ci-dessus. A notre avis, une autre action, plus agissante, doit être cherchée dans la pénétration plus aisée vers l'amont de l'onde-marée, grâce à la diminution de résistance hydraulique de la partie aval et de la partie centrale du lit maritime de l'Escaut, notamment sous l'action de dragages intensifs pour permettre l'arrivée de navires de tonnage de plus en plus élevé à Anvers. Il en est résulté, d'abord, un accroissement du volume de l'onde. Cette augmentation a accru de la même quantité le volume de flot et le volume de jusant, égal au volume de flot augmenté des apports d'amont. Ceux-ci n'étant pas modifiés, le volume de jusant a, proportionnellement, moins augmenté que le volume de flot.

Une autre conséquence de la diminution de la résistance hydraulique du fleuve a été un redressement de la face amont de l'onde-marée, du fait de l'accroissement de la célérité de son sommet dont la hauteur était augmentée. La durée du gagnant dans les sections d'amont a donc diminué, tandis que la durée du perdant augmentait. La durée du flot (durée déjà beaucoup plus petite que celle du jusant) dans ces sections a de ce fait aussi diminué, tandis que la durée du jusant augmentait. Les vitesses de flot, provenant d'un volume de flot proportionnellement plus augmenté que le volume de jusant, et s'écoulant sur un temps de flot réduit, ont donc augmenté plus que celles de jusant (qui n'ont pas nécessairement augmenté).

Les formules de débit solide sont généralement du type :

$$\psi U^2 (U^2 - U_0^2)$$

U_0 étant la vitesse pour laquelle commence le mouvement.

On en arrive donc à la situation suivante : le débit solide dû au courant de flot augmente notablement parce que U^2 et $U^2 - U_0^2$ augmentent à chaque instant et que $U^2 - U_0^2$ est positif pendant un plus long laps de temps. Au contraire le débit solide de jusant diminue pour des raisons inverses de celles qui viennent d'être données (fig. 18). Dans le cas considéré, la situation est

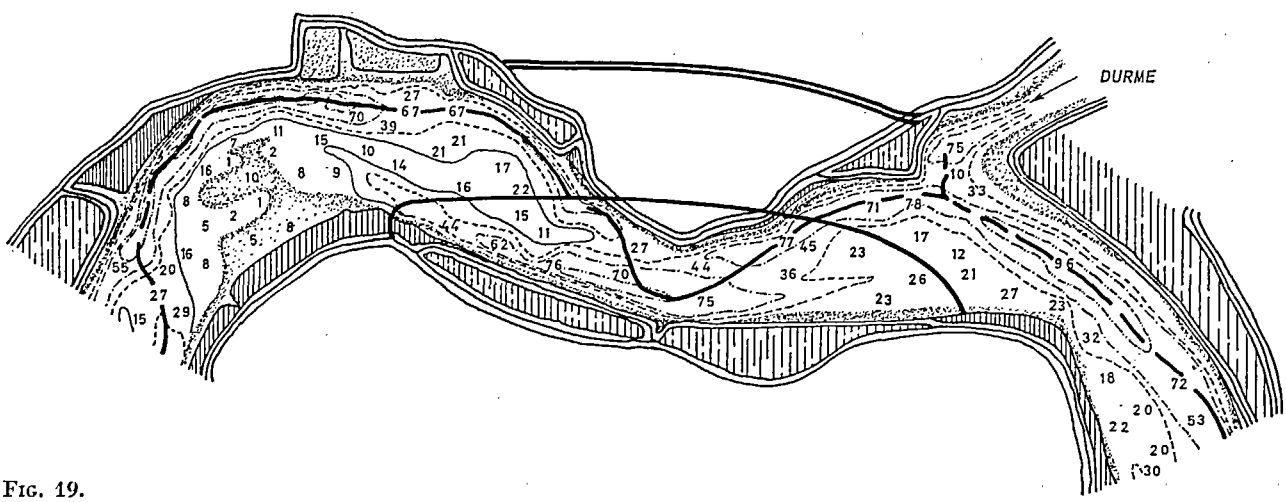

FIG. 19.

aggravée par le fait qu'à relativement faible distance de l'embouchure de la Durme dans l'Escaut, ce fleuve reçoit le Rupel, qui doit amener des quantités assez notables de substances solides. L'accroissement exposé ci-dessus de la puissance de transport du courant de flot trouvera dans ces matériaux une source d'alimentation.

Avant 1914, le lit de la rivière était sensiblement en équilibre, avons-nous vu. On voit maintenant que le débit solide dirigé vers l'amont a augmenté, alors que celui allant vers l'aval a diminué. La conclusion est donc que le lit de la rivière va se remplir d'alluvions.

Il est une autre raison que nous croyons bon d'ajouter, car des cas semblables doivent souvent se présenter. L'embouchure de la Durme dans l'Escaut a été modifiée comme l'indique la figure 19. Autrefois (avant 1912), le courant de flot se trouvait devant une bifurcation aux deux branches quasi symétriques par rapport au lit aval du fleuve. Le partage des sédiments entre l'Escaut et son affluent suivait le partage des débits liquides, particulièrement important vers l'Escaut supérieur (fig. 19). La transformation de 1912 a donné à la Durme une entrée placée latéralement sur l'alignement général de l'Escaut. Les considérations théoriques du début de cette étude montrent que le débit solide sera particulièrement attiré par cette entrée latérale : d'où aggravation de la sédimentation dans la Durme.

L'exemple précédent a été particulièrement exposé pour montrer l'influence considérable de modifications souvent peu importantes du lit des estuaires. L'action des marées peut d'ailleurs être renforcée par l'influence du vent, qui en provoquant un gonflement de la mer vers les embouchures peut accroître la marée et ses effets dans des proportions considérables (action des marées-tempêtes).

ACTION DES COURANTS LITTORAUX ET DE LA HOULE

Dans ce qui précède, on n'a guère insisté sur les apports maritimes. Il n'empêche que l'entrée des courants de flot, dans les divers types de pénétration de la mer que nous avons considérés, se produit certainement en amenant des sédiments marins. La proportion de ces sédiments varie évidemment avec les rivières. Pour le fleuve Hudson dont il a été question ci-dessus, la proportion des sédiments d'amont est de 76 %, le reste comprenant des sédiments remaniés et d'autres venant de l'océan.

Dans d'autres cas cependant, la proportion des sédiments augmente, et c'est notamment le cas lorsque des courants littoraux viennent alimenter le flot entrant en matériaux solides.

Ces courants littoraux peuvent être dus à l'action de la marée. Ainsi, sur les côtes hollando-belges, des courants littoraux renversent leur direction avec la marée. Ces courants peuvent aussi être dus à de grands courants océaniques venant lécher les côtes. Ils peuvent aussi provenir de l'action de la houle qui peut pousser l'eau contre les rivages, cette eau s'échappant ensuite de l'une ou l'autre façon. L'action du vent peut donner lieu à des actions directes plus importantes.

Ces courants littoraux, quelle que soit leur origine, joueront souvent un rôle important dans la sédimentation des estuaires, des deltas, en y amenant des quantités notables de matériaux solides d'origine marine.

Rien n'est en fait modifié au régime purement hydraulique de ces estuaires, mais les courants littoraux amèneront des provisions sans cesse renouvelées de matériaux que les courants de flot, particulièrement dans les coins salés, transporteront vers l'amont à des distances parfois considérables vers l'intérieur.

Il semble bien que l'examen de quelques exemples permettra de mieux se rendre compte de l'action de ces courants littoraux souvent combinée avec celle de la marée, de la houle et du vent.

Delta de L'Escaut, de la Meuse et du Rhin aux Pays-Bas

Les mesures de transports solides de ces fleuves semblent indiquer que les quantités de sédiments qu'ils amènent à la mer ne sont pas très considérables.

Par contre, depuis la Flandre française, sur la côte belge et en face du delta mentionné, le fond de la mer du Nord présente des masses de sable considérables dont l'origine n'est pas bien connue. Sous l'influence de la marée, les courants en face des côtes indiquées sont dirigés du sud-ouest vers le nord-est pendant le flot, mais se renversent pendant le jusant. Ces courants provoquent des mouvements de sable que les mesures faites indiquent comme très légèrement prédominants du sud-ouest vers le nord-est. En face du débouché des fleuves, les masses de sable dont il a été question sont quelque peu étalées vers le large et les divers bras de fleuves y découpent un delta sous-marin dont les limites d'extension présentent en plan une courbure dont le centre est vers l'intérieur des terres.

Si l'on examine l'action de la marée sur les diverses ouvertures du delta, on observe un phénomène assez curieux qui n'est pas sans action sur le mouvement des sédiments (Van Veen, 1931).

Quand un fleuve débouche en mer par deux bras CA et CB (fig. 20) et que la direction de propagation de la marée est sensiblement parallèle à la côte, en allant de A vers B, on constate que les pentes superficielles ont une tendance très nette à être plus marquées dans CA que dans CB. C'est ce que montrent, dans la figure 21, les courbes représentatives des variations de hauteur dues à la marée, en fonction du temps, en chacun des points A, B, C; on y voit que, dans les hypothèses adoptées (qui sont celles du delta hollandais), les pentes dans AB — données par le quotient de la différence des hauteurs en un même instant en A et en B, par la distance AB — sont très supérieures à celles de BC, données par un quotient analogue. Dès lors, AB sera le bras prépondérant, où le mouvement des matériaux solides

sera en général suffisamment assuré pour ne pas provoquer de sédimentation dangereuse. Il n'en est pas nécessairement de même dans le bras BC, où la puissance de transport limitée facilite la sédimentation, surtout si les dispositions d'entrée de ce bras tant en B qu'en C sont telles que les courbures y facilitent l'entrée des matériaux solides (voir début de l'article). Si C s'éloigne vers l'intérieur, l'action ci-dessus décrite est évidemment réduite. Cette action est par contre d'autant plus forte que les lignes d'égale marée sont plus rapprochées. Il peut se produire aussi que le delta, sous-marin ou non, soit constitué de nombreux bras en éventail. Si le point C de la bifurcation de ces bras est assez proche des extrémités des bras vers la mer, on peut facilement se rendre compte que les mouvements liquides seront les plus favorisés vers les branches d'extrémité de l'éventail et réduits vers le centre (fig. 22). D'où les bras les moins puissants au centre, avec les conséquences qui en résultent pour la sédimentation. On peut se demander si une action analogue ne s'est pas produite dans le delta du Pô, où la marée se déplace du nord vers le sud. La marée n'est évidemment pas très forte, mais elle a certainement favorisé l'écoulement vers les branches nord en réduisant l'importance des débouchés sud.

D'autre part, le déferlement des vagues soulevées par un vent venant souvent d'ouest ou du sud-ouest provoque un autre phénomène. Ce déferlement met du sable en suspension et le déplace vers les passes de l'est (qui, d'après les considérations ci-dessus sont les plus faibles et les plus tranquilles). Le sable amené tend à s'y déposer contre l'extrémité sud-ouest des îles situées le plus à l'est de l'éventail. Ces îles ont donc tendance à croître vers le sud-ouest.

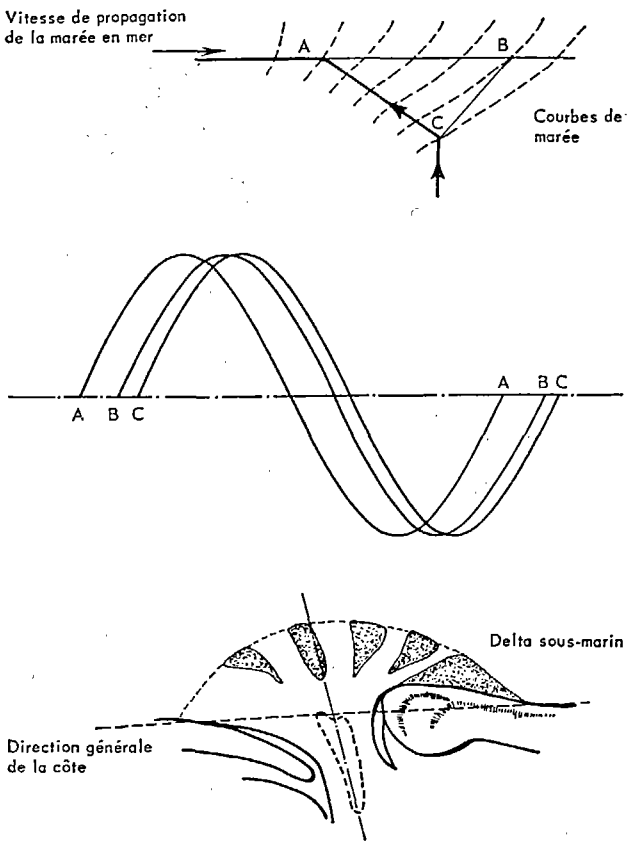

FIG. 20, 21, 22 (d'après Van Veen).

Cas de l'estuaire du Karnafuli dans le Pakistan (fig. 23)

Les conditions d'amont (sur lesquelles on s'est étendu au début de cette étude) avaient provoqué la naissance d'un bras débouchant à gauche du bras principal (vers l'est). D'autre part, un courant littoral toujours dirigé de l'est vers l'ouest n'a pas tardé à alimenter en matériaux solides, d'origine marine, le courant de flot pénétrant dans le nouveau bras, cette entrée étant d'ailleurs favorisée par la courbure du courant entrant. L'insuffisance du courant de jusant dans ce bras secondaire n'a pas réussi à chasser les sédiments introduits et ce bras s'est ensablé en partant du rivage. Le déplacement vers l'est de l'embouchure de la Ruzizi dans le lac Tanganyika peut s'expliquer par l'action d'un courant lacustre dû à la houle et par le déferlement de celle-ci.

Autres considérations sur l'action de la force de Coriolis dans les estuaires

On a vu que cette force pouvait créer une sorte de distorsion de la répartition de la salinité dans les estuaires avec comme conséquence une distorsion analogue dans le dépôt des sédiments. Mais cette force de Coriolis peut exercer une autre influence dans tous les larges estuaires. On sait que cette force, correspondant à une accélération d'intensité égale à

$$2 v \omega \sin \varphi$$

(où v est la vitesse du courant, ω la vitesse de rotation de la terre et φ la latitude) s'exerce vers la droite de la direction du courant dans l'hémisphère nord. Cette accélération aura une influence analogue à celle d'une courbure, en provoquant une érosion vers la rive droite par rapport à la direction du courant. Du fait de l'inversion du sens de ce courant par la marée, cette action s'exercera alternativement sur les deux rives, pouvant notamment y amener la production de mouilles dans les alignements du fleuve. Dans les régions courbes, elle pourra accentuer l'érosion des rives concaves. Il faut cependant éviter de tirer des conclusions trop rapides de la similitude d'action de l'accélération de Coriolis et de celle de l'accélération normale v^2/ρ. On a cru en effet pouvoir dire que l'action de la force de Coriolis est identique à celle d'une courbure de rayon ρ donné par la relation :

$$\frac{V^2}{\rho} = 2 V \omega \sin \varphi$$

FIG. 23. Estuaire du Karnafuli (Pakistan).

V étant la vitesse moyenne. Mais l'érosion due à l'accélération de Coriolis est en effet due à des courants plongeants dont on peut établir l'existence en utilisant des équations analogues aux relations (1), (2) et (3) données en début d'article, en y remplaçant v^2/ρ par $2\,v\,\omega \sin \varphi$. On arrive ainsi à la conclusion que le courant est d'autant plus plongeant et l'érosion par conséquent d'autant plus forte que la différence.

$$\int_A^B 2\,v\,\omega \sin \varphi\, ds - \int_{A'}^{B'} 2\,v'\,\omega \sin \varphi\, ds \qquad (5)$$

est plus grande.

AB est une ligne normale au courant de surface de vitesse v et A′ B′ est une ligne normale au courant de fond de vitesse v'. Pour une courbure de rayon ρ, la différence correspondante serait :

$$\int_A^B \frac{v^2}{\rho}\, ds - \int_{A'}^{B'} \frac{v'^2}{\rho}\, ds \qquad (6)$$

Quand on s'impose comme on l'a dit ci-dessus

$$\frac{V^2}{\rho} = 2\,V\,\omega \sin \varphi$$

les rapports des deux différences (5) et (6) à cette valeur commune valent respectivement :

$$\int_A^B \frac{v}{V}\, ds - \int_{A'}^{B'} \frac{v'}{V}\, ds$$

et

$$\int_A^B \frac{v^2}{V^2}\, ds - \int_{A'}^{B'} \frac{v'^2}{V^2}\, ds$$

qui sont nettement différents l'un de l'autre.

L'assimilation proposée n'est donc pas acceptable.

SÉDIMENTATION EN DEHORS DU LIT DU BRAS

Le prolongement des différents bras d'un delta a souvent pour effet d'enserrer entre certains d'entre eux des étendues assez considérables de mer qui peuvent être transformées en lagunes si les atterrissements des bras voisins tendent à se joindre par une sorte d'action en tenaille. Tout l'ancien delta du Mississippi vers La Nouvelle-Orléans, Bâton-Rouge et même au-delà renferme des quantités de lacs de plus ou moins grande étendue dus à l'avancement préférentiel des terres le long des bras.

La comparaison des situations du delta du Pô en 1812 et en 1935 donne aussi un bel exemple d'une telle formation entre le Pô di Gnocca et le Pô delle Tolle (fig. 24).

Ces lagunes peu profondes en général se comblent plus ou moins rapidement par les sédiments de leurs affluents, plus encore par les apports marins tant qu'elles restent ouvertes à la mer, par la végétation, et aussi lors des débordements et des ruptures de digues des bras qui les ont enserrées. Leur fond arrive finalement à émerger, mais il reste souvent en contrebas des eaux (surtout des hautes eaux) des bras voisins.

On a vu d'ailleurs que le prolongement des bras en mer a pour effet de relever le fond du lit des cours d'eau. D'autre part, le sol des régions où se forment les deltas est souvent sujet à des affaisements dus soit aux tassements, soit à des mouvements tectoniques (c'est le cas, semble-t-il, d'une bonne partie du sol des Pays-Bas, par exemple). De plus, le niveau de la mer subit des fluctuations et c'est ainsi qu'il semble bien qu'au cours

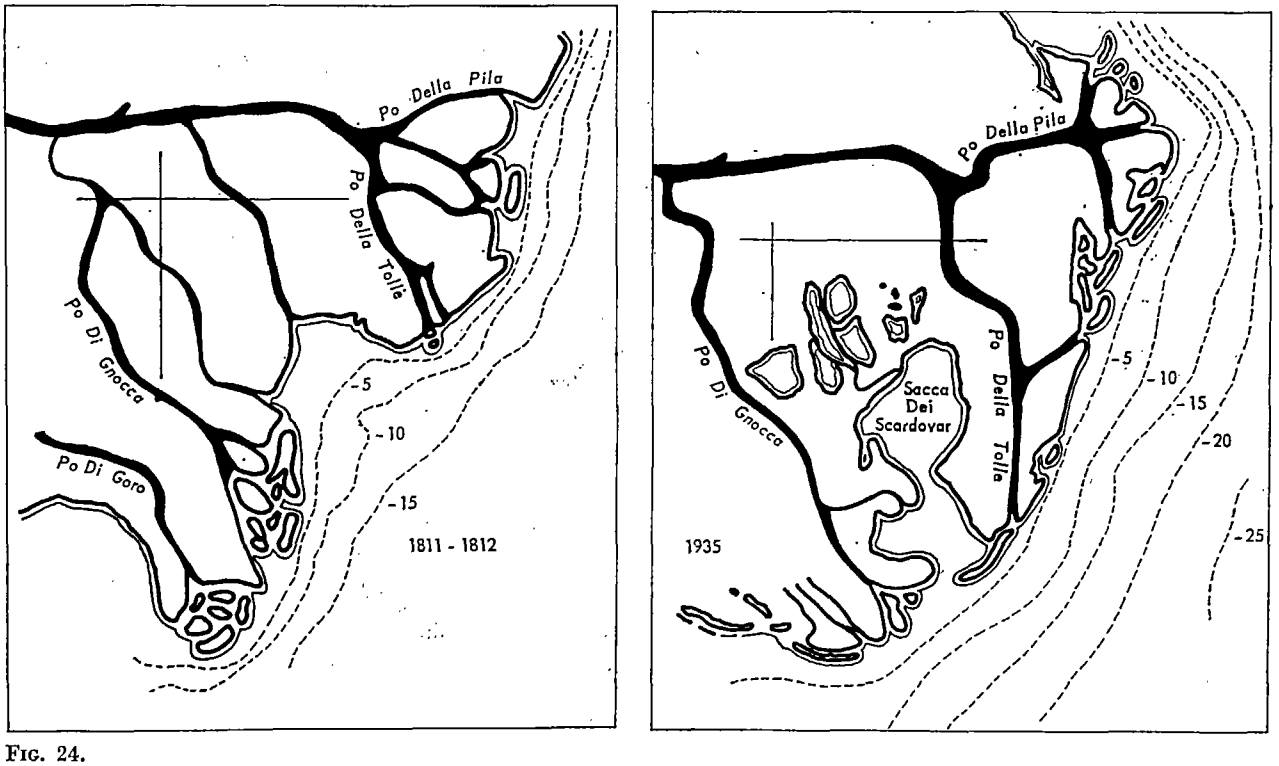

FIG. 24.

du siècle actuel, ce niveau se relève de façon sensible (12 centimètres en cinquante ans à Venise, par exemple, mais le phénomène est général).

Les dépôts continueront à se produire sur ces étendues en contrebas. Les dépôts en provenance de la mer seront en général très fins et donneront naissance à des argiles. Les zones de végétation y donneront naissance à des bancs de tourbe. Des lits entrecroisés de sables et même de graviers indiqueront l'influence des apports des bras voisins.

Ainsi se sont formés les sols de la Flandre maritime en Belgique et de nombreuses régions des Pays-Bas. Du temps de l'occupation romaine, la côte s'avançait en mer un peu plus que de nos jours (en Flandre); puis un affaissement du sol ou un relèvement du niveau de la mer a permis l'entrée de la mer derrière la côte, transformée en une série d'îles allongées. La végétation primitive de ces régions envahies a donné naissance à des bancs de tourbe, tandis que les sédiments marins très fins se déposaient dans ces eaux assez tranquilles pour donner naissance à l'argile bleue.

Les bras qui avaient autrefois enserré les lagunes se sont à leur tour comblés par des apports de sable et de graviers lorsque de nouveaux bras se sont formés par ruptures des digues des anciens bras : comme on l'a vu ci-dessus la disposition en plan des bras leur attire plus ou moins de matériaux solides qu'ils ne peuvent pas toujours évacuer; d'où leur comblement.

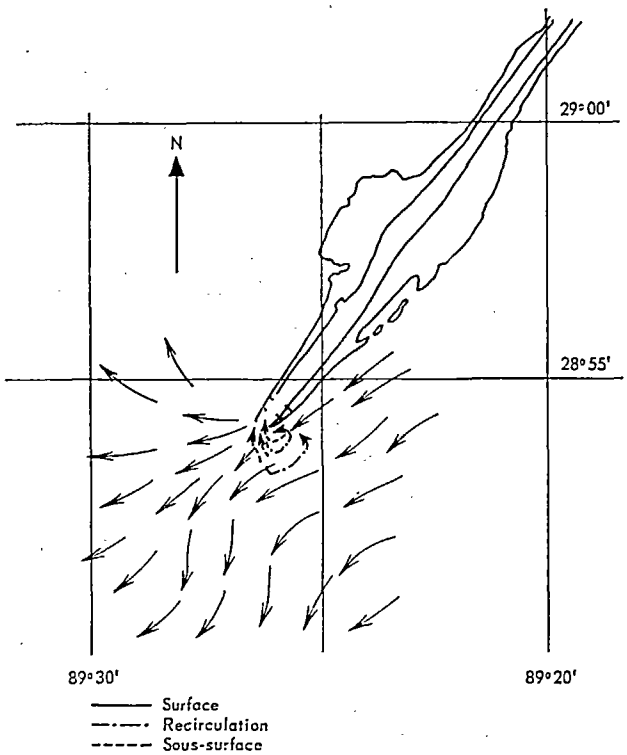

Fig. 25.

Après un certain temps, les terrains ainsi formés donnent d'ailleurs lieu à des phénomènes d'un autre ordre. Les sols argileux et tourbeux des lagunes continuent à se tasser au cours des années, tandis que les bras remblayés naturellement par les sables et graviers gardent sensiblement leur niveau. On en arrive donc finalement à une véritable inversion du relief, les anciens lits au remplissage de sable sont en saillie sur le sol voisin affaissé des anciennes lagunes.

Les différents bras de l'embouchure proprement dite du Mississippi donnent un exemple bien caractéristique de l'influence de courants littoraux sur la sédimentation dans un delta. Ces courants venant d'une direction générale est n'exerce guère d'action sur les sédiments de la Pass a Loutre, dont l'orientation générale est opposée à ces courants. Tout au plus ceux-ci provoquent-ils une répartition en éventail plus ouvert de ces sédiments, les profondeurs étant assez uniformément réparties sur l'ensemble de cet éventail et restant insuffisantes pour la navigation (fig. 25).

Pour les deux autres passes au contraire, leur embouchure est frappée transversalement par les courants en question, ce qui repousse les sédiments dans la région tranquille à l'ouest des débouchés, provoquant une sédimentation assez intensive dans cet espace à demi-fermé.

Une étude de R. Silvester (1962) sur les courants littoraux chargés de sédiments peut donner de premières indications intéressantes sur les apports qu'on peut leur attribuer dans les régions deltaïques.

CONCLUSION

Les considérations qui précèdent montrent toute la complexité du problème du mouvement des sédiments dans les zones deltaïques. Leur étude exige une connaissance approfondie des quantités de sédiments amenées de l'amont par les fleuves, de celles qui peuvent être amenées du côté de la mer par les courants littoraux dus aux conditions océanographiques, à la marée, au vent et à la houle. Le dépôt, le transport et l'érosion de ces sédiments seront d'autre part influencés par la dynamique du fleuve, par la salinité et ses divers modes de propagation, par la marée et les courants dont il est question ci-dessus.

Semblables études exigeront une connaissance profonde des lois de l'hydraulique et de l'hydrologie, s'appuyant sur des essais de laboratoire toujours très difficiles à conduire.

Summary

Problems of sedimentation in deltas and their estuaries (L. J. Tison)

When a river laden with silt flows into the sea, the deceleration resulting from the spreading out of the current naturally causes sediments to be deposited, and there they remain unless sea currents, due to tides or other factors, carry them away.

The curves described by the river waters as they flow into the sea produce rising currents which come from the bottom and therefore have a high silt content. The splaying of the current causes deceleration and the rapid deposit of the coarser sediments; these form a kind of dike which gradually moves seaward. When these natural dikes are breached by flood-waters, arms are formed which, though initially minor projections, may grow larger, or may close up, depending on local conditions and particularly on stream diversions.

When the river is in spate, the finer sediments are deposited between these two arms, and if the ends of the latter converge, their pincer movement may transform the space between them into lagoons, which then become flood-plains as a result of sedimentation.

Furthermore, the prolongation of the projecting arms reduces the gradient of the river, which has certain effects on the deposit of sediments.

A number of deltas are then studied in the light of these theoretical explanations.

The foregoing remarks, however, would be true only of rivers flowing into fresh-water seas without tides or coastal currents.

In point of fact, the interaction of fresh and salt waters has a tremendous influence on sedimentation and the phenomena caused by this interaction will vary according to how far the salt and fresh waters mix. If there is very little mixture, the salt water will advance in the form of a wedge under the fresh water of the estuary. The wedge moves backwards and forwards with the tide and also under the influence of the upstream waters. This overlapping area is a very propitious one for sedimentation, because of the flocculation of suspended sediments in the salt water and also because of the deceleration in this zone.

In other estuaries, where a greater degree of mixture exists, there is a layer of water with a steeply rising saline content between the fresh surface water and the sea water flowing beneath.

Examples are given of both types of flow mentioned above with their effect upon sedimentation (Mississippi, Po, Hudson, Chesapeake). There are also rivers where the mixing process goes so far that the isohalsines become almost vertical. On the basis of the principle of diffusion a distribution of salinity is deduced and its effect upon sedimentation described. A rather curious case of sedimentation in the upstream parts of an estuary is also quoted.

The influence of coastal currents is chiefly visible in the solid matter which they bring with them and which increases the sedimentation rate. Examples of this process are given and make it possible, *inter alia*, to explain changes in delta mouths.

Sedimentation outside the arms of the delta, the formation and evolution of lagoons, etc., are also studied and illustrated with examples.

These examples also make it possible to study the effects of the Coriolis force, the influence of winds and swells, and so forth.

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Hydrology and formation of river-mouth bars

V. N. Mikhailov

INTRODUCTION

Due to the effect of river sediment material discharge and action of the sea the river-mouth (or delta-channel) bars (shoals), formed by sediment deposits, are commonly the most variable delta areas. Seaward advance of a delta and extension of its river channels occur principally in bar areas. As a result of shoaling, instability of bottom relief and intensive sediment accumulation within river channels, the delta-bar areas become a serious obstacle to navigation and, therefore, necessitate a comprehensive investigation of bay-mouth bars.

This report deals with some problems associated with the hydrological régime and the formation of bars in the mouths of plain rivers.

MAJOR ACTIVE FACTORS

Bars are characteristic of the greater majority of rivers entering seas and lakes. Aquaintance with cartographic, geological and geomorphological data, as well as with sea- and lake-bottom topography, shows that river-mouth bars are formed in various physiographical and hydrological environments.

The formation of a bar, its size and shape depend on the intensity of sea and freshwater interaction processes taking place at the mouth of a river.

Factors such as sea currents, wave action, tidal currents, sea-level rise, etc., can in a number of instances prevent the formation of a large delta. Nevertheless, bars are usually formed even under similar environmental factors and the bar features can be traced at almost any river mouth.

Many factors affect the formation of bars. There is still no clear evidence of their relative significance. Despite the fact that under varying environmental conditions the influence of one factor or another may differ, it is necessary to point out that entirely different rivers reveal many common features in the process of bar formation. Therefore, the existence of certain general regularities common to the process of bar formation can be expected in any environment.

The presence of these general regularities is explained by the fact that the main factor predetermining the formation of a bar is the river water and the sediment discharge. To form a bar in the mouth of a river, it is sufficient to have a water flow that can transfer river sediments. The action of the river-water flow and the sediment discharge builds up a background upon which the effect of other factors, deforming and shaping an already formed bar, is displayed.

Wave action in the process of bar formation has a complex and contradictory effect. It may sweep away sediment formations created by the river action, and build up new ones. Observations carried out at a number of river mouths have shown that whilst sweeping out bar formations, wave action broadens them and increases water depths over the bars. Under the influence of storms bars move towards the land. Wave action washes away the shoreline and a portion of the delta banks and bars, transports the washed-out material and accumulates it at some other place, thus forming shoals and sand-bars. The wave action changes the configuration of an initial bar formed by river action. In a number of instances the action of waves can block up the mouth of a river with banks.

A similar destructive and shaping effect on bars can produce tidal and ebb-flood currents varying in their direction. Like the wave action, these cause migration and redeposition of bar sediments at bar areas thus causing changes in water depth above the bar and sedimentation deposits within navigable channels.

Under similar environmental conditions the balance of the sediment deposit at the bar area is of great importance. If the transportation power of the longshore sediment flow caused by the action of waves and sea currents exceeds the volume of sedimentation discharged by the river, the bar is destroyed. Otherwise, it grows intensively. Evidently, therefore, the adjust-

ment of the river sediment discharge may be viewed as a radical step to control sediment deposit at bar areas.

The growth of vegetation on the top of the sediment formations built up by a river flow enables them to consolidate. While hampering the further movement of sediments carried by river flow, the vegetation cover facilitates the bar development, promotes the bifurcation of the river channel and contributes to the growth of the delta. In some deltas the vegetation cover grows so actively that it seems to have a decision effect on the delta formation.

There is no doubt that such passive factors as coastline configuration, sea-bottom relief underlying the bar, geological structure, etc., play no less an important role in the formation of bars.

The author has tried to investigate the mechanism of bar formation in the case when a river flow is the sole or decisive factor. Among the factors determining bay-bar formation of a river-mouth bar, the river current is the most prominent one; a similar approach to the problem permits the study of the process which constitutes the background upon which other factors display their effect. In the long run it will help to estimate more precisely the role of other factors and, above all, the role of the wave action and tidal currents.

THE ROLE OF RIVER FACTORS IN THE FORMATION OF RIVER-MOUTH BARS

Laboratory experiments

The investigation of regularities in the formation of a river-mouth bar can be greatly assisted by model testing. Such tests have been carried out by the author at the Laboratory of Channel Processes, U.S.S.R. Academy of Sciences.

At the outset the task was to investigate the velocity structure of a freshwater stream discharged into a reservoir and to determine its role in the process of bar formation. The experiments have shown that there is no regularity in the distribution of stream velocities in the river flow: with the widening of the flow velocities decrease both along and across the stream. Decrease of velocities along the stream starts from the mouth entrance and develops in a relation near to the exponential, while across the stream it proves to follow a parabolic curve (close to the mouth) and a curve approaching the Gaussian probability curve (away from the mouth). The application of hydraulic methods allows an estimation of the field velocity of the stream to be made (Mikhailov, 1959).

Material transported by the model stream, deposited in full conformity with the stream velocity structure: the decrease of the velocity along the stream resulted in the formation of a bar in front of the mouth, and a non-uniform distribution of velocities across the stream led to a formation of sand shoals. The formation of bars and sand shoals developed simultaneously and

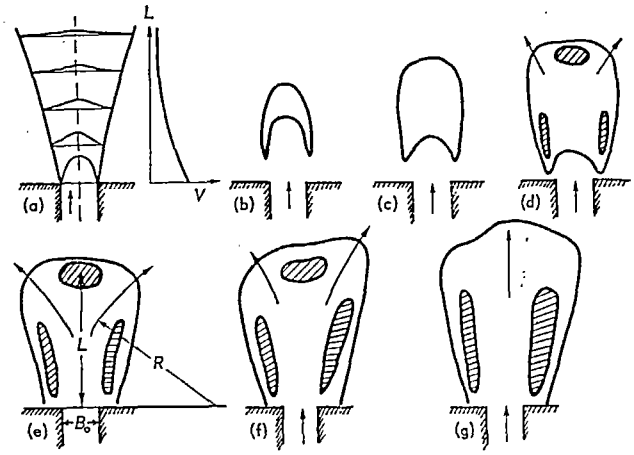

FIG. 1. Diagram of bar and island formation process in the mouth of a flow (plotted according to laboratory experiments data); (a) to (g) show the successive stages of the process.

there appeared a "finger" of river sediments deposited in the reservoir (Fig. 1a, b and c). The intensity with which the bar grows is proportional to the amount of sediment discharge and is inversely proportional to the angle of the shore slope in the reservoir.

The object of further experiments was to reveal how a relief formed at the mouth of a stream influences the structure of a river-water flow. Bottom drifts deposited in the upper areas of the stream brought about a rise of the channel bottom and the appearance of longitudinal and transverse slopes of water surface above the bar. The presence of a transverse slope led to the smoothing of the flow when it passed over the bar, the widening of the bar and a subsequent bifurcation of the flow and the formation of an island in the middle (Fig. 1d and e).

Bars in river mouths

Field observations of river mouths carried out by the State Institute of Oceanography in the Soviet Union and analysis of data on foreign rivers show that at places where the river discharge is a decisive factor, the process of bar formation at the mouth of natural rivers is similar to that obtained under laboratory conditions. Prominent examples of the development of the bottom relief in the mouth of rivers formed at open shores as a result of the breaking-through of beach barriers are the Vistula river mouth and the mouth of the Sulak river falling into the Caspian Sea.

The process of bar formation at the mouth of other rivers which have sufficiently large water and sediment discharge is similar to the above. The mouth of the Danube, the Mississippi, the Amu-Darya, the Kuban and other rivers (Bates, 1953; Mikhailov, 1958, 1962; Samoilov, 1952) were also formed in a similar way.

The bars at the mouth of similar rivers are composed of river-sand deposits and only at normal water stages

are they covered with silt. There is a distinct relationship between the flow velocities of river current and the composition of sediment particles deposited over the bar (larger particles accumulate at places where current velocities are greater). The discharge of a river at its various stages plays an important role in the process of bar formation: bars are formed principally at a high-water stage. All the above-mentioned phenomena support the assumption that river factors occurring at the mouth of a majority of rivers play a principal role. Therefore, river-mouth bars should be viewed primarily as formations built up by river action. This observation allows two major conclusions to be drawn: (a) the channel régime of the water flow should influence the channel régime of the bar; (b) the hydraulic methods of computing channel deformations may be applicable to the bar.

The role of the river-sediment discharge

The river-bed load plays an active part in the formation of river-mouth bars. A bar composed of a bed load is similar in shape to rapids with gentle upstream and steep downstream slopes, and, as in rapids, the shoaling of bar areas takes place during the flood stage. As bars are formed mainly during the flood stage and as during this period the velocities of currents passing over the bar are relatively high, the suspended sediment material is not deposited over the bar but is swept farther seaward. This is proved by the field measurements of current velocities taken at river mouths. During the normal stage suspended sediments can deposit over the bar area and higher in the upstream direction.

The sand-banks shifting from place to place within the river channels can destroy the bar by creeping over it. Having studied the river-channel depth régime

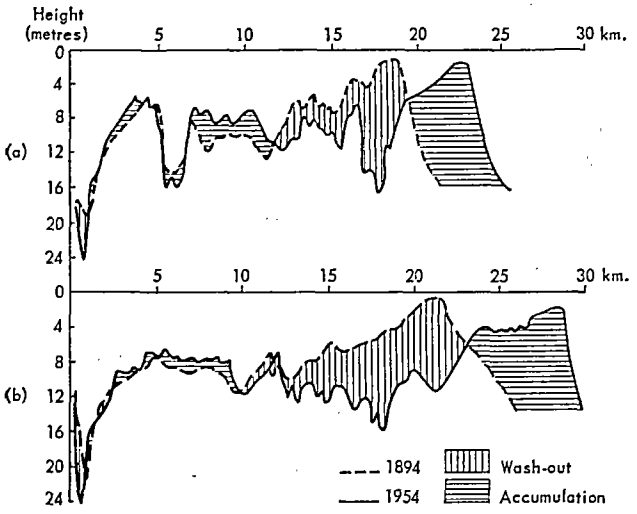

FIG. 2. Advance of bars seaward at the mouths of the (a) Ochakov and (b) Old Istanbul channels in the Danube delta.

and the expected fluctuations of the river discharge, it is possible to forecast the water-depth régime over the bar.

With the accumulation of sediments at the mouth of a stream, the bar moves seaward and the stream channels elongate (Fig. 2). The bar displacement of the three heterogeneous zones of channel-shaping activity is involved with: (a) the accumulation and rise of the channel bottom; (b) the scouring of the bar upstream slope; and (c) the accumulation of the sediment material on the bar's seaward slope.

Morphometric characteristics of the river-mouth bar

It is well known that there exists a relationship between the morphometry of a river channel and the dynamics of its stream. The author has made an attempt to apply hydraulic methods when computing the morphometric characteristics of a river-mouth bar (Mikhailov, 1958). It was found that the increase of the flow velocities and the water discharge led to the increase of both the minimum attainable radius of the river-stream curvature in the bar area and the distance from the mouth to the ridge of the bar. This relationship was produced theoretically:

$$\frac{L}{B_0} \sim A \left(\frac{h_0}{B_0}\right)^{1/3}$$

where L stands for the distance to bar ridge or island; h_0 and B_0 are the depth and width of the channel at the mouth entrance; A is the ratio coefficient which depends but very little on the sediment composition.

The development of the formula required the use of: (a) parameters for longitudinal and transerve flow equilibrium over the bar

$$J_{\text{long.}} = \frac{V^2}{C^2 h} \text{ and } J_{\text{trans.}} = \frac{V^2}{gR}$$

where J is the longitudinal and transverse slopes of the water surface over the bar, V and h are average velocity and stream depth, C is the Shezi coefficient, R is radius of stream curvature; (b) the approximate relationship between $J_{\text{long.}}$ and $J_{\text{trans.}}$

$$\frac{J_{\text{long.}}}{J_{\text{trans.}}} \sim k \frac{B_0}{L};$$

(c) the approximative relationship between distance to the bar L, channel width in the mouth B_0 and radius of stream curvature R:

$$L \sim \sqrt{RB_0}.$$

On the basis of laboratory data and cartographic materials of a number of river mouths (Fig. 3) an empirical relationship approaching the theoretical ($A \sim 12$, exponent 0.37) was found which proves the close correlation between the dynamics of the river flow and its bottom relief in the mouth. Thus obtained the empirically deduced relationship shows that streams with greater values of the ratio width to depth form

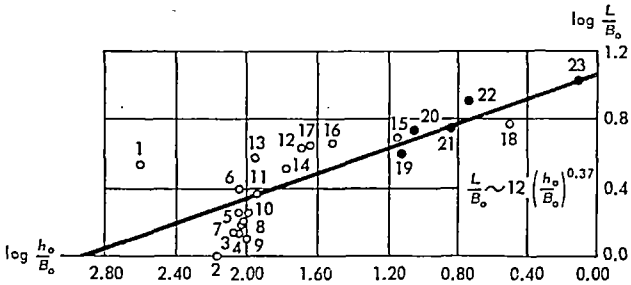

FIG. 3. Diagram of relationship between relative distance to the bar or island $\frac{L}{B_0}$ and relative depth of channel $\frac{h_0}{B_0}$.
○ = field survey data, ● = laboratory data.

1. Mississippi.
2. Vistula, 1916.
3. Vistula, 1952.
4. Vistula, 1897.
5. Vistula, 1946.
6. Vistula, 1941.
7. Vistula, 1948.
8. Vistula, 1951.
9. Vistula, 1946.
10. Vistula, 1947.
11. Vistula, 1932.
12. Vistula, 1924.
13. Golden Gate.
14. Peresipsk mouth of Kuban.
15. Skladkovsk mouth of Kuban.
16. Kuban.
17. Western Dvina.
18. Trubezh.
19. Experiment N° 9.
20. Experiment N° 10.
21. Experiment N° 8.
22. Experiment N° 4.
23. Bates' observation.

the bar and the island nearer to the mouth than those with smaller values of the $\frac{B_0}{h_0}$ ratio. Therefore, the shapes of channels in river mouths are geometrically dissimilar and depend on the size of a river. This relationship may be utilized for approximate computations of channel deformations in river mouths with a predominant influence of river discharge and in the construction of river-mouth models.

The radius of the stream curvature over the bar is also associated with hydraulic characteristics of the flow (Mikhailov, 1958). For natural river mouths the following relationship is valid: $R \sim kQ^{0.5}$.

The author used the above relationships and the data obtained by Leopold and Maddock (1953) for rivers for the equation $h \sim h_1Q^{0.4}$, $B \sim k_2Q^{0.5}$, where B and h are the depth and the width of a channel, Q is channel-shaping volume of water.

The periodic processes in deltas

Laboratory experiments have shown that the processes of bar formation are of a periodic nature. An intensive widening of a bar which results in a bifurcation of the river flow and the formation of an island is further replaced by the straightening and the narrowing of the flow and, finally, by the washing-out of the island (Fig. 1f and g). In these environmental conditions a new bar is formed farther seaward in the same direction. Later, the bar widens again and forms a new island, etc. If an island so formed is somehow protected from the washing-out, two channels each with a bar in its mouth are developed on each side of the island. Under laboratory conditions the island was consolidated by growing a grass cover over its surface (the experiment was temporarily discontinued).

Similar periodic processes of widening and narrowing the flow passing over the bar were recorded in the mouth of natural rivers (the Danube, the Vistula and others). It is rather difficult to observe these processes—frequent and precise measurements being required—which, however, are indispensable for forecasting the navigable conditions of the water depth over the bar.

If the island built up in a bar area is not washed out, two short, symmetrical channels are usually formed. The subsequent process of delta development follows along the lines of periodic formation of new islands and the growth of a number of channels. During this process the symmetry of the initial division of the flow passing over the bar is usually rapidly disturbed. The principal cause of this phenomenon is probably the inability to maintain for a long period of time a constant volume of water through each newly formed channel; this should inevitably lead to the straightening of the greater-capacity channel. It is due to the fact that the minimum permissible radius of flow curvature in the greater-capacity channel is also larger. This circumstance may explain the present state of the Keil channel mouth in the Danube river delta. Out-of-date maps show that the initial delta channels bifurcated symmetrically. Later, one of the channels received a greater volume of water flow and straightened, while the other, through having lost its water flow, turned its course at a more obtuse angle with respect to the base channel.

As a result of this activity the traces of symmetric bifurcation of the water flow into delta channels gradually diminish beginning from the delta apex towards its more recent marginal areas.

CONCLUSIONS

As a result of analysis and extrapolation of field observations and specially planned laboratory experiments one may reach the conclusion that the formation of bars and river-mouth islands is characteristic of the majority of river mouths, located in various physiographic environments, and that their formation is predetermined principally by the dynamics of the river flow and the volume of the river-sediment discharge. Other factors (wave action, tidal currents, growth of vegetation, coagulation of suspended sediments, etc.) deform or shape the bar formed by the river flow, and facilitate or retard its development.

During the first phase of the bar-forming activity in an environment where the effect of river factors is predominant, the velocity structure of a river stream is of a decisive significance, as the bar and the river-mouth sand shoals are formed in conformity with this structure. At a later stage the newly-created forms of

relief reveal their own effect on the river stream by widening the stream and even by bifurcating it into separate channels. At this phase of bar development it is possible to speak of the interaction processes taking place between the river stream and the forms of relief created by the latter. If bar-consolidating factors are not involved, the process of bar formation develops along the lines of periodic widening and narrowing of the river flow.

The position of an already formed bar or island in the mouth of a flow is predetermined by the velocity structure of the river stream entering the sea. By utilizing hydraulic methods, relationships were derived which facilitated the calculation of the distance to the bar and the radius of the flow curvature. The testing of these relationships based on the data of field surveys undertaken in the mouth of a number of rivers and laboratory experiments confirm their validity.

Résumé

Hydrologie et formation des barres dans l'embouchure des fleuves (V.N. Mikhailov)

L'analyse et l'extrapolation des résultats obtenus au moyen d'observations sur le terrain et d'expériences de laboratoire spécialement conçues à cette fin permettent de conclure que la formation de barres et d'îlots dans l'embouchure des fleuves est une caractéristique de la plupart des embouchures situées dans divers milieux géomorphologiques et que cette formation est prédéterminée principalement par la dynamique du fleuve et par le volume des sédiments que celui-ci dépose. D'autres facteurs (action des vagues, courants de marée, végétation, coagulation de sédiments en suspension, etc.) déforment et façonnent la barre formée par l'écoulement des eaux du fleuve et en facilitent ou en retardent l'évolution.

Au cours de la première phase de la formation de la barre dans un milieu où l'effet des facteurs fluviaux prédomine, la distribution des vitesses d'un cours d'eau revêt une importance capitale, car la barre et les bancs de sable de l'embouchure se constituent conformément à cette distribution. Par la suite, les formes de relief nouvellement créées font sentir à leur tour leurs effets sur le fleuve en l'élargissant, voire en le scindant en plusieurs bras distincts. A ce stade de la formation de la barre, on peut dire qu'une interaction se produit entre le fleuve et les formes de relief qu'il a créées. Si aucun facteur n'intervient pour renforcer la barre, la formation de celle-ci a pour effet d'élargir et de rétrécir périodiquement le cours d'eau.

La position d'une barre ou d'un îlot déjà formés dans l'embouchure d'un fleuve est prédéterminée par la distribution des vitesses du cours d'eau qui pénètre dans la mer. Au moyen de méthodes hydrauliques, l'auteur a obtenu des relations permettant de calculer la distance de la barre et le rayon de courbure du cours d'eau. L'exactitude de ces relations a été confirmée par les résultats d'enquêtes effectuées sur le terrain dans un certain nombre d'embouchures, ainsi que par des expériences de laboratoire.

Discussion

V. N. Nagaraja. Dr. Mikhailov's paper is interesting, bringing out briefly the mechanism of the formation, development, stabilization, etc., of bars in estuaries. The author's findings are based on his observations of the river mouths of the Danube, Vistula and the Sulak in the U.S.S.R., all discharging into seas with insignificant tidal action.

When, on the other hand, strong tides and waves occur at the river mouth, the shoal-forming processes undergo great changes. A nearby example is the River Hooghly joining the Bay of Bengal. But for the great tidal activity the river would have been dead long ago. There are many other rivers which are similarly maintained by tidal action.

Since all important rivers are used for various purposes—navigation, industrial establishments, etc.—new forces come into play. Navigation channels, jetties and other structures, dredging and spoil disposal, etc., exert great influence on the river-mouth bars. Littoral currents also play an important part.

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Mud transport studies using manganese as an accompanying element under temperate and tropical climatic conditions (Western Europe, Amazon area and Chao-Phya river area in Thailand)

A. J. de Groot

In many parts of the world the problems of origin and transport of alluvial sediments from the rivers to their delta areas and the adjacent coastal areas are very important. Geologists are interested in these problems in connexion with the genesis of soils derived from these sediments. Civil engineers build constructions to avoid siltation of channels to harbours and the harbours themselves. A detailed knowledge of the direction of movement of the sediments is necessary in this respect. Finally, the land reclamation expert needs information about quantities and texture of sediments he tries to gain in coastal areas for empoldering new land.

Sediments may consist of coarse- (sand) and fine-grained fractions. The method described in this paper is only appropriate for studying the origin and transport of fine-grained sediments. The transport of mud (fine-grained fraction < 16 microns) is investigated by the use of manganese as an accompanying element. The deposits from different rivers and locally from the sea bottom are distinguished by different Mn content.

METHODS OF INVESTIGATION

A main division of the Mn compounds in a sediment can be made into exchangeable Mn and higher oxides.

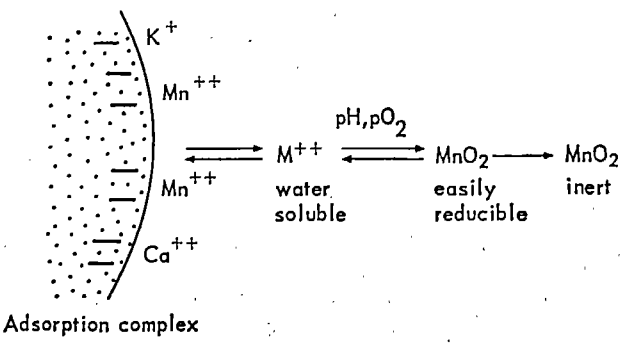

FIG. 1. Conversions between inorganic forms of manganese in a sediment.

The exchangeable Mn is bound as manganous ions to the adsorption complex (clay minerals and organic colloids) of the sediment and is the most mobile form apart from small amounts of Mn in the enclosed water. The higher oxides form a sequence of compounds with varying reactivity. They can be distinguished by their oxidizing power.

The conversions between the Mn forms are schematized in Figure 1.

The redox equilibrium between the mobile forms of Mn and easily reducible Mn is controlled by the pH and the oxygen concentration in the sediment.

The oxidation of bivalent Mn, as indicated in Figure 1, can take place by purely chemical processes, at pH values above 4.9, whereas microbiological oxidation may occur at pH values ranging from 4.8 to 8.9.

During transport in aerated river or sea water the mud cannot lose Mn, because the latter is almost exclusively present as insoluble higher oxides. Most of it is present in the grain-size fractions 0-35 microns. In connexion with this preferred occurrence in the fine fractions, a linear relationship is found between the contents of Mn (both total and reducible Mn) and the fraction < 16 microns (as a percentage of the $CaCO_3$-free mineral constituents), if the origin of the sediments is the same.

In Figure 2 these relationships are demonstrated for freshly deposited sediments of the River Ems and for sediments of the Flemish banks, the latter being mud deposits on the bottom of the North Sea before the shore of Belgium and the south-western Netherlands. The relationships between the Mn content and the fraction < 16 microns are extrapolated to 100 per cent of the fraction < 16 microns. An Ems deposit containing 35 per cent of the fraction < 16 microns, corresponds to the amount CE (= DF) of Mn in the fraction < 16 microns and the amount EF in the sand (fraction > 16 microns). Commonly the Mn composition of the fine fraction is represented by the line OA^1. The extrapolated Mn content is represented by O^1A^1.

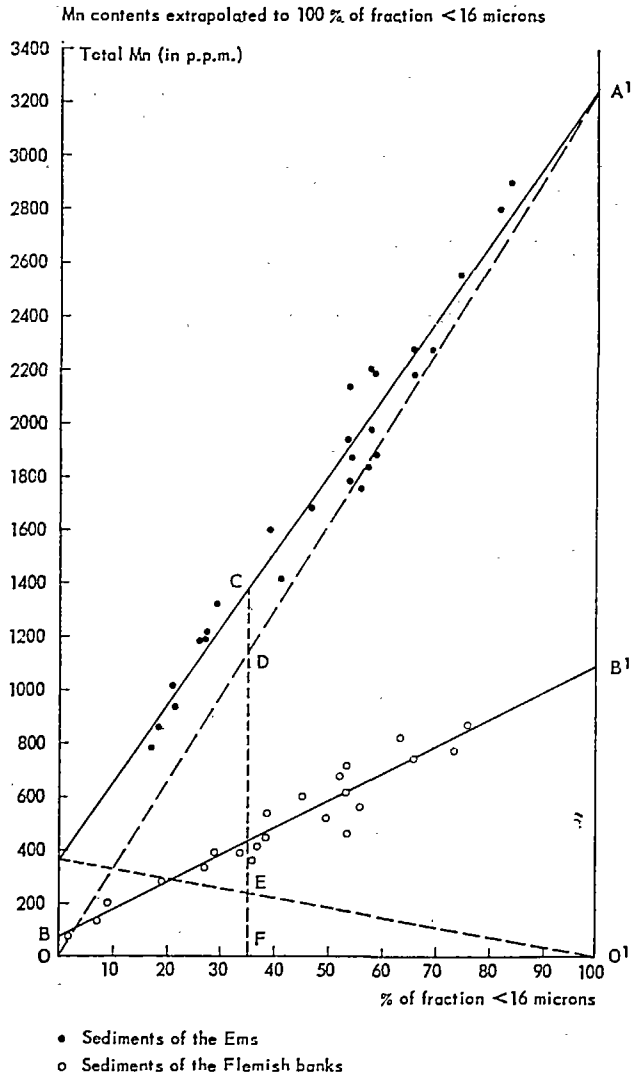

FIG. 2. Linear relationship between manganese content and percentage of fraction < 16 microns.

For mutual comparison of different kinds of mud the contents O^1A^1 are now used. Single values to characterize whole groups of CO-genetic sediments with different granulometric compositions are thus obtained.

The coefficients of the regression equation

$$y_l = \bar{a}x + \bar{b},$$

representing the relationship between the Mn content and the fraction < 16 microns, are computed as follows:

$$\bar{a} = \frac{n\Sigma xy - \Sigma x \Sigma y}{n\Sigma x^2 - (\Sigma x)^2} \qquad \bar{b} = \frac{1}{n}(\Sigma y - \bar{a}\Sigma x)$$

where n represents the number of analysed samples; x and y are, respectively, the contents of the fraction < 16 microns and the Mn contents of the samples concerned. Now the extrapolated Mn content O^1A^1 ($y_{l\,100}$) is derived from the regression equation by substitution of the value $x = 100$.

After deposition, reduction can take place, to a smaller or larger extent depending on the redox potential of the environment. At the moment of deposition of the sediment the redox potential is high, generally about 400 mV. If sedimentation occurs in stages on a low-lying surface such as the sea bottom or the lower parts of artificial settling beds (artificial systems of banks of brushwood and channels ensuring sedimentation) microbial attack of the sediment gives rise to a lowering of the redox potential (down to — 100 mV). Consequently the higher Mn oxides are reduced to the exchangeable form. Depending on the salt content of the surrounding water the Mn^{2+} ions can be more or less exchanged by the dissolved salt ions, leading to a lower Mn content of the sediment. However, in freshwater environments the Mn content decreases very slowly. Table 1 clearly demonstrates the contents of exchangeable Mn, calculated per 100 per cent of the fraction < 16 microns, of reduced sediments in relation to the salt content of the water.

TABLE 1. Contents of exchangeable Mn, calculated per 100 per cent of the fraction < 16 microns, of reduced sediments dependent on the salt content of the water

Locality	Exchangeable Mn (p.p.m.)	Cl (‰)
Settling beds, Uithuizerwadpolder	106	16
Submerged land of Saaftinge	407	8
Settling beds, Haringvliet	528	2
Sub-layers, eastern Biesbosch	618	0
Top layers, eastern Biesbosch	748	0

When mud is deposited on more elevated parts (higher than low-tide level) such as river forelands, reed marshes, willow coppices and marine forelands, no reduction of the deposits takes place. In consequence the sediments do not show an appreciable loss of Mn.

Irrespective of any loss of Mn, the relationship between Mn contents and percentages of the fraction < 16 microns remains approximately linear, so that the characteristic values (for 100 per cent of the fraction < 16 microns) can still be determined in the same way as for freshly deposited material.

ANALYTICAL METHODS

Total Mn

The amounts of total Mn are determined according to Kurmies (1953) by treating the air-dry sediment with NH_4NO_3, dissolving the ash in HNO_3, oxidation of the Mn to $HMnO_4$ and finally by measuring the colour in a spectrophotometer at 525 nm.

The above-mentioned method is rather elaborate. Recently a series of analyses were carried out with the

Philips Automatic X-Ray spectrometer. The sediments could be pressed to tablets with a pressure of 200 kg. per cm.^{2} without further preparation. The tablets were analysed with a LiF crystal rotating in air. The total time for analysis of a sample is 240 seconds with an accuracy of 1-2 per cent.

$CaCO_3$

The fraction < 16 microns is expressed as a percentage of the $CaCO_3$-free mineral constituents, hence the content of $CaCO_3$ must be estimated. The content is determined according to the Scheibler method modified by Bruin (1937). The air-dry sediment is shaken with diluted hydrochloric acid (about 8 per cent), measuring the volume of the evolving CO_2 in comparison with the volumes of CO_2 liberated from a sequence of known amounts of pure $CaCO_3$.

Organic matter

Expressing the fraction < 16 microns as a percentage of the mineral $CaCO_3$-free constituents, the content of organic matter must also be estimated. The analyses are carried out according to Mebius (1960). The organic matter is oxidized by a solution of $K_2Cr_2O_7$, the excess $K_2Cr_2O_7$ titrated back with a solution of Mohr's salt, using N-phenylanthranilic acid as an indicator.

Redox potential

The redox potential is an important factor to distinguish recent sediments from older ones, the recent deposits with high redox potentials being most useful for studying the mud transport problems. The potential is measured in a suspension of the sediment under nitrogen atmosphere, using a platinum and a calomel-electrode. The details of the method have been described by the author (De Groot, 1963).

Fraction < 16 microns

The contents of the fraction < 16 microns are determined with the pipette method according to Hooghoudt (1945).

GENERAL RESULTS IN WESTERN EUROPE

There are distinct differences in the Mn contents of the different sources of mud along the coasts of England, Belgium, the Netherlands and Western Germany. If the Mn content of the fine-grained sediments of the River Thames is taken as 1, the mud entering the North Sea through the Straits of Dover contains twice the amount, the rivers Scheldt, Meuse and Rhine 4 times, the River Ems 5 ½ times and the River Elbe even 7 times the amount of Mn of the River Thames (Fig. 3). Very low Mn contents (one-third) are found in the old alluvial clay layers on the sea bottom off the coast of Schleswig Holstein, resulting from the reduction of the sediments

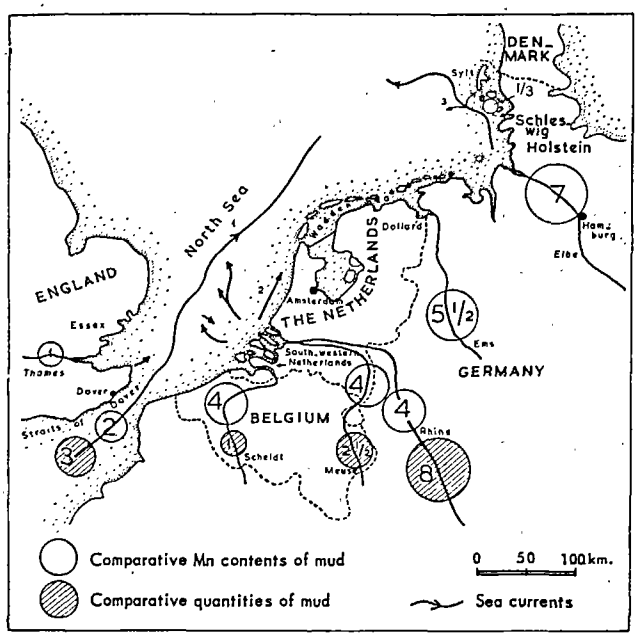

FIG. 3. Sources of mud and water movements in the North Sea area.

and exchange of the Mn^{2+} ions by the salt ions of the sea-water which has been going on for many centuries already.

By examining several thousands of samples from the above-mentioned area, a detailed insight was obtained into the origin and transport of mud from the rivers and locally from the sea and shallow floor to the areas outside the dikes along the various coasts. The great differences in contents of Mn in the deposits examined were very helpful in this respect.

Apart from one detail, only a few main details as regards these investigations will be given in this paper. For full details the reader is referred to the author's papers (De Groot, 1963, 1964).

Sedimentation along the continental coast is not effected by the mud of the River Thames. This is obvious, for example, from the fact that water from the Thames is separated from the water along the coast of the continent by the ocean water penetrating via the Straits of Dover (sea current 1 in Fig. 3). Therefore, the distribution of mud from the Thames is restricted to the Essex coast in England.

The supply of mud to the south-western Netherlands occurs both from the south (via the Straits of Dover) and from the River Scheldt.

The Meuse and the Rhine transport their fine-grained sediments (mainly originating from the Rhine) in a northerly direction into the western part of the Dutch Wadden Sea (sea current 2 in Fig. 3). The mud is partly deposited temporarily in the western Wadden Sea (with partial loss of its Mn content as a consequence of reduction and exchange), from where it is further

transported in an easterly direction over the Wadden Sea flats, and partly enters into the Ems-Dollard estuary.

The mud transported by the River Ems is deposited in a limited area of the Dollard, as will be further outlined in the next section.

The Elbe mud is carried by the sea currents (3 in Fig. 3) in a north-westerly direction and has primarily only a limited influence on the sedimentation along the western shore of Schleswig Holstein. Thus in the middle of this coast the Elbe mud, containing more Mn than any other mud investigated, is mixed to a considerable extent with the old alluvial clay (very low Mn contents) off the coast. Farther to the north the sea current branches off towards the southern point of the island of Sylt in a north-easterly direction (see Fig. 3), giving rise to a more important influence of the River Elbe on the sedimentation with high Mn contents just south of the Danish frontier.

DETAIL OF THE INVESTIGATIONS IN WESTERN EUROPE

A detail is given here from the investigations along the continental coast, especially relating to the River Ems. The Dollard area, being a part of the estuary of the Ems (Fig. 4), receives fine-grained sediments from the Dutch Wadden Sea, originating from the Rhine and Meuse, and from the Ems. As described in the preceding section, the Mn content of the Ems mud is higher than the contents of the Rhine and Meuse material. Moreover the Rhine and Meuse material entering the Dollard lost part of its Mn during temporary sedimentation in the Dutch Wadden Sea. In Figure 4 the Rhine and Meuse material enters the Dollard area by tidal currents from the left side, the Ems sediments coming from the right.

In this figure the Mn contents relative to the fraction < 16 microns (= 100 per cent) are given of freshly deposited sediments on the artificial settling beds, the contents of marine forelands and of the polders embanked from forelands. Passing along the Ems and farther along the Dollard from the Ems mouth via Nieuw Statenzijl to the Punt van Reide, the high Mn contents of the original Ems muds decrease constantly in the muds, marine forelands and polders. In this way the significance of the Ems in the sedimentation of the Dollard is clearly shown.

The marine forelands have lower Mn contents than the freshly deposited muds, because the forelands are partly composed of reduced material eroded from deeper layers of the artificial settling beds. The polders lost part of their Mn after embankment from the marine forelands.

RESULTS IN TROPICAL AREAS

River Amazon, South America

In recent times more serious attention has been paid to the origin of the fine-grained sediments deposited along the Guiana coast in South America. The general opinion is that these sediments are carried to the sea by the Amazon and transported by the Caribbean sea current to the Guiana coast (Fig. 5).

Bakker (1963), however, believes that the sediments in the shallow area of Guiana are partly of a more eastern origin. He bases his conclusion on the fact that the mineral compositions of the Amazon sediments (kaolinite and halloysite) and the shallow deposits (illite, montmorillonite and kaolinite) off the Guiana coast differ. The illite and montmorillonite of the recent coastal sediments of Guiana would at least partly come from the western coast of Africa. The sea

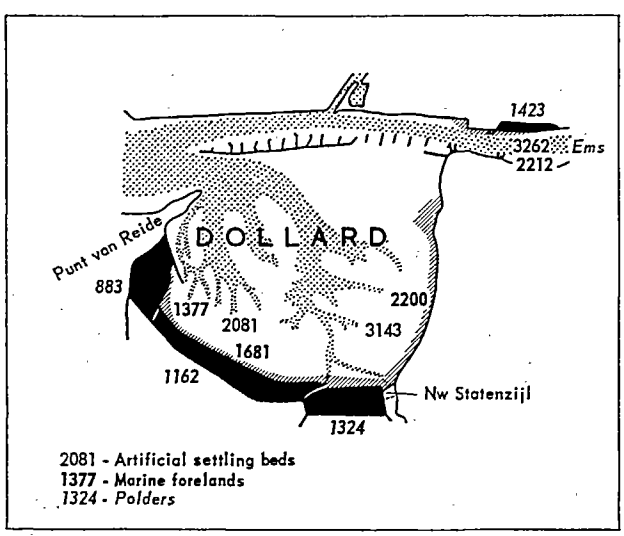

FIG. 4. Influence of the Ems on sedimentation in the Dollard.

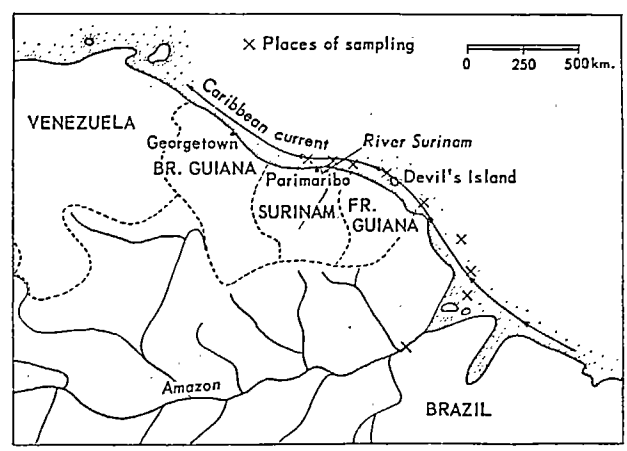

FIG. 5. Sampling area of Amazon sediments.

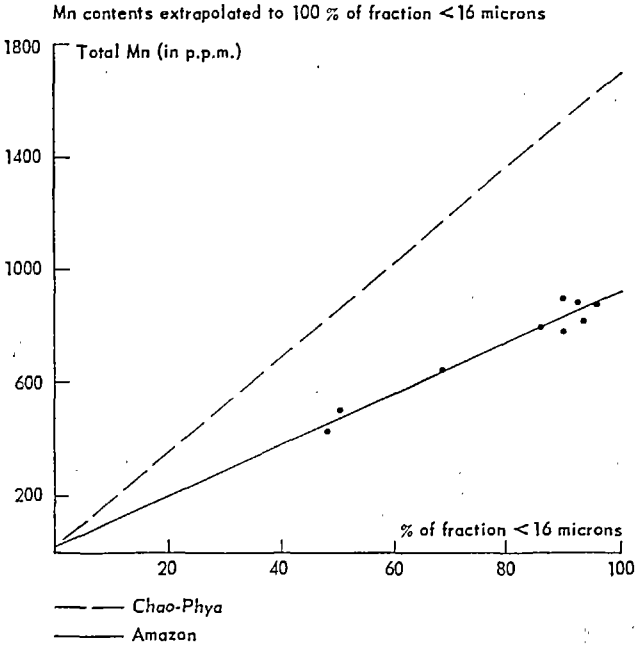

FIG. 6. Manganese content of sediments of the Amazon area.

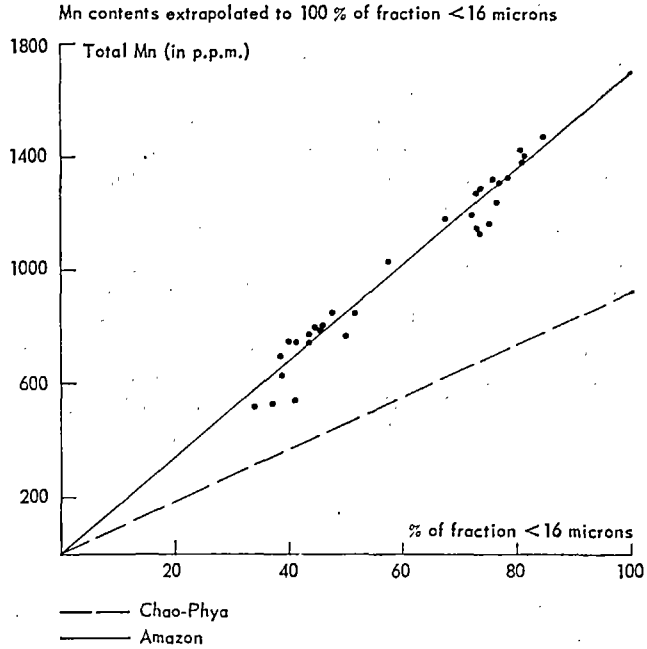

FIG. 7. Manganese content of sediments from the Chao-Phya.

currents of the Atlantic Ocean would be responsible for the transport to the Guiana coast.

In collaboration with L. J. Pons (at present with the Department of Soil Survey in Paramaribo), a very limited investigation has been carried out in the Amazon area. A set of samples has been taken from the River Surinam via Devil's Island into the estuary of the Amazon, as indicated in Figure 5. The Mn contents of these samples have been plotted against the fraction < 16 microns in Figure 6. There is a linear correlation between the dots, having its beginning in the origin of the graph, pointing to a uniform composition of the sediments examined. Taking into account the small amount of samples, no clearer indication could have been obtained for a direct transport of Amazon mud to the coast of Guiana.

The investigations in the Amazon area will be amplified by the examination of the mineralogical composition of the sediments and with analyses of sediments of the interior of the Amazon area.

River Chao-Phya, Thailand

Instructed by the Thailand office of the Netherlands Engineering Consultants (NEDECO), investigations are in progress in which the Mn method is used for studying the movement of mud from the Chao-Phya to the bar of the river in the Bay of Thailand and vice versa. These investigations are carried out in connexion with siltation problems of the harbour of Bangkok. It is impossible, however, to give full details of these investigations in this paper, because a report to the Thailand authorities has not yet been made available. Only the principles of the investigations will be given here.

The Mn contents of the fine-grained sediments deposited by the Chao-Phya are given in Figure 7. Here again a linear relationship exists between Mn contents and percentages of fine-grained fractions. In the same figure the line for the Amazon deposits has been given, just as the Chao-Phya line has been plotted in Figure 6. The Mn contents of the Amazon and of the Chao-Phya are not very high compared with the contents of European rivers.

The mud load of the Chao-Phya depends greatly on the time of the year, as may be seen from Figure 8. During certain months there is even a reverse movement of mud from the bar to the river.

To get an insight into the movements of mud from the river mouth to the bar, over the bar and from the

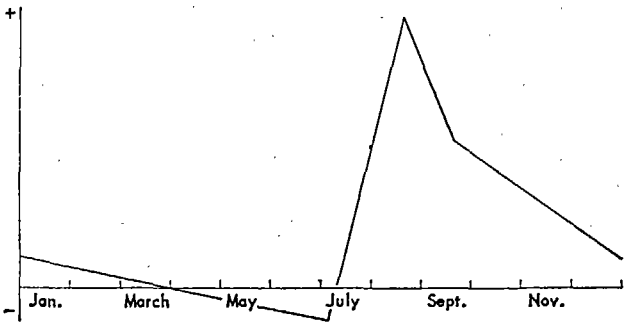

FIG. 8. Mud discharge of the Chao-Phya.

bar to the river, samples have been taken periodically from a network of sites. A simplified example of the results of the Mn analyses in a series of samples at a certain time has been given in Figure 9.

The Mn contents in this figure are relative amounts, expressed as percentages of the Mn contents of fresh mud deposited by the river (at equal contents of the fraction < 16 microns).

In this way a survey is obtained from the freshness of the mud in different places on the bar. A lower Mn content points to less recent sedimentation or to sedimentation material eroded at an earlier date. By making several of these Mn maps in the course of a year and comparing them with each other, conclusions can be drawn concerning the movement and sedimentation of mud on the bar and in the river-mouth area.

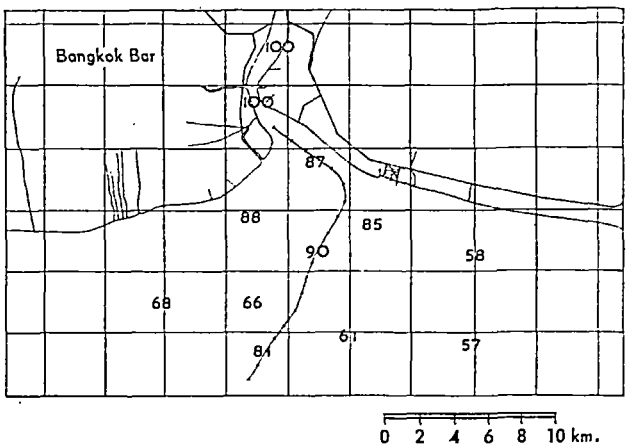

FIG. 9. Relative manganese content of sediments from the Bangkok bar.

Résumé

Le manganèse indicateur de transport de limon en climats tempérés et tropicaux (A. J. de Groot)

Le manganèse peut contribuer à déterminer l'origine du limon (fraction inférieure à 16 microns) ainsi que la direction vers laquelle il est transporté le long des côtes de régions tempérées et tropicales.

L'auteur décrit en détail les méthodes physiques et chimiques. Ensuite il donne un aperçu des résultats obtenus en étudiant l'origine et le mouvement des sédiments fins dans les eaux côtières de la mer du Nord, en Europe occidentale. En outre, il discute des possibilités d'appliquer cette méthode aux régions tropicales (Amazonie et Thaïlande).

Discussion

A. Q. M. B. KARIM. In which forms and in which fractions do the insoluble manganese oxides in the sediment occur? Does any relation exist between the amount of manganese and the type of clay minerals in the sediments?

A. J. DE GROOT. In very young soil in which pedogenesis has not yet taken place, the manganese is mainly present in the granulometric fractions < 50 microns as coatings around the clay particles. The amount of manganese per unit of weight of the fractions is quickly diminishing with the increase of the dimension of the fraction.

After pedogenesis, however, there is to a certain extent a shift of the manganese from the finer to the coarser fractions (solution and recrystallisation of the manganese in the form of concretions).

No relationship between the amount of manganese and type of clay minerals is known.

J. HERVIEU. (1) How many samples must be taken to study the sediment transport of a river to its bar and in reverse? (2) How much time does the estimation of manganese content take?

A. J. DE GROOT. (1) Studying the transport of the fine-grained fractions in the course of a year with a total of 500 samples will give a sufficient insight into the problem. (2) During an eight-hour working day about fifteen analyses of total manganese, by using a colorimetric method, can be done. By using the Röntgen fluorescent method the capacity can be speeded up to 100 samples a day.

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Sur les caractéristiques texturales et minéralogiques des sédiments récents et des sols alluviaux dans le delta du Mangoky (sud-ouest de Madagascar)

J. Hervieu

INTRODUCTION

C'est sur le versant occidental malgache (bassins sédimentaires de Majunga et de Morondava) que les témoins de la sédimentation détritique récente et d'origine continentale sont les plus étendus, en particulier dans les régions littorales et le précontinent (côtes de transgression).

La dissymétrie même du relief général de l'île entraîne une extension plus grande des bassins versants des rivières occidentales. L'agressivité du milieu morpho-climatique (climat tropical à saison sèche marquée et végétation de savane herbeuse dégradée ou de pseudo-steppe) est cause de phénomènes d'érosion accélérée. Enfin la mer a transgressé jusqu'à une altitude supérieure de quelques mètres au-dessus du niveau marin actuel dans de profondes vallées postpliocènes, d'où un remblaiement important, pouvant atteindre 100 m d'épaisseur, favorisé par l'extension du plateau continental et les faibles pendages des couches sédimentaires vers le canal de Mozambique.

L'alluvionnement récent est plus apparent sur la côte ouest proprement dite, avec formation de deltas typiques ou embryonnaires, que sur la côte nord-ouest, où de profondes vallées en « rias » ne sont encore que partiellement comblées.

CARACTÈRES GÉNÉRAUX DU DELTA DU MANGOKY ET DE SON BASSIN VERSANT

Situation et extension géographique

Le delta du Mangoky est situé dans la région sud-ouest de Madagascar (sous-préfecture de Morombe), un peu au nord du 22e parallèle (fig. 1). C'est le plus important de l'île par son étendue : plus de 1 500 km².

Ce delta unilobé progresse actuellement dans une direction N-NO. Le front deltaïque convexe s'étend sur environ 65 km et fait saillie de 15 km sur la ligne de rivage actuelle. La pente moyenne de la plaine deltaïque est de 0,75 pour 1 000.

Hydrologie

Le fleuve Mangoky s'individualise peu avant sa sortie du massif cristallin central, au confluent de ses deux principaux tributaires : Matsiatra et Mananantanana. Son bassin versant s'étend sur une superficie d'environ 59 000 km² dont plus de 60 % dans le massif cristallin, le reste étant situé dans la couverture sédimentaire gréso-calcaire (permo-trias-jurassique essentiellement). L'hypsométrie du bassin se présente comme suit :

4 % à moins de 200 mètres d'altitude
13 % de 200 à 400 mètres
16 % de 400 à 600 mètres
15 % de 600 à 800 mètres
28 % de 800 à 1 000 mètres
10,5 % de 1 000 à 1 200 mètres
7,9 % de 1 200 à 1 400 mètres
4,6 % de 1 400 à 2 000 mètres.

L'altitude moyenne du bassin est 775 mètres

Les crues se produisent de novembre à mars avec un débit moyen de l'ordre de 3 000 m³/s, le débit moyen en période d'étiage (octobre) étant seulement de 80 m³.

Climat

La nature, le mode de dépôt et l'évolution pédologique des alluvions fluviatiles sont en relations directes avec les facteurs climatiques régnant dans le delta et son bassin versant. Il s'agit d'un climat de type tropical normal, à saison sèche bien marquée.

Le delta et la plus grande partie du bassin versant sédimentaire sont situés dans la zone climatique dite de la côte ouest, où la pluviométrie moyenne annuelle ne dépasse guère 800 mm, mais peut descendre dans la région littorale aux environs de 400 mm en année sèche, avec de fortes irrégularités d'une année à l'autre. La température moyenne annuelle varie entre 24 et 27 °C. Les affluents dans cette zone, exception faite pour ceux s'alimentant en partie sur les hauts plateaux, ont un

cours instable ou sont à sec une partie de l'année. Le ruissellement est brutal et moins généralisé que sur les hauts plateaux cristallins. La végétation climacique est une forêt sèche tropophile en grande partie détruite et remplacée par une brousse arbustive secondaire ou une prairie haute de graminées sur les sols les plus riches, par une pseudo-steppe plus ou moins arborée sur les sols pauvres.

Le bassin versant métamorphique appartient à la zone climatique dite des hauts plateaux, qui, par suite de la variation brutale d'altitude, correspond approximativement à la limite socle ancien - sédimentaire. La pluviométrie moyenne annuelle varie entre 1 et 2 mètres et augmente de l'ouest vers l'est. La température moyenne annuelle varie entre 18 et 22 °C. Dans cette zone, le régime saisonnier des pluies est contrasté mais assez régulier, le ruissellement généralisé est très important. Les actions anthropiques y sont considérables (en particulier action des « feux de brousse ») et la grande épaisseur de la couverture d'altération favorise une érosion parfois spectaculaire (« lavaka »). La couverture végétale se réduit le plus souvent à une pseudo-steppe de graminées avec de rares survivances de la végétation forestière d'origine (forêt basse sclérophylle).

CARACTÉRISTIQUES TEXTURALES ET MINÉRALOGIQUES DE LA SÉDIMENTATION RÉCENTE

Les chiffres et les appréciations qui figurent dans cette synthèse ne sont pas le résultat d'observations isolées, mais sont basés sur un nombre important d'analyse

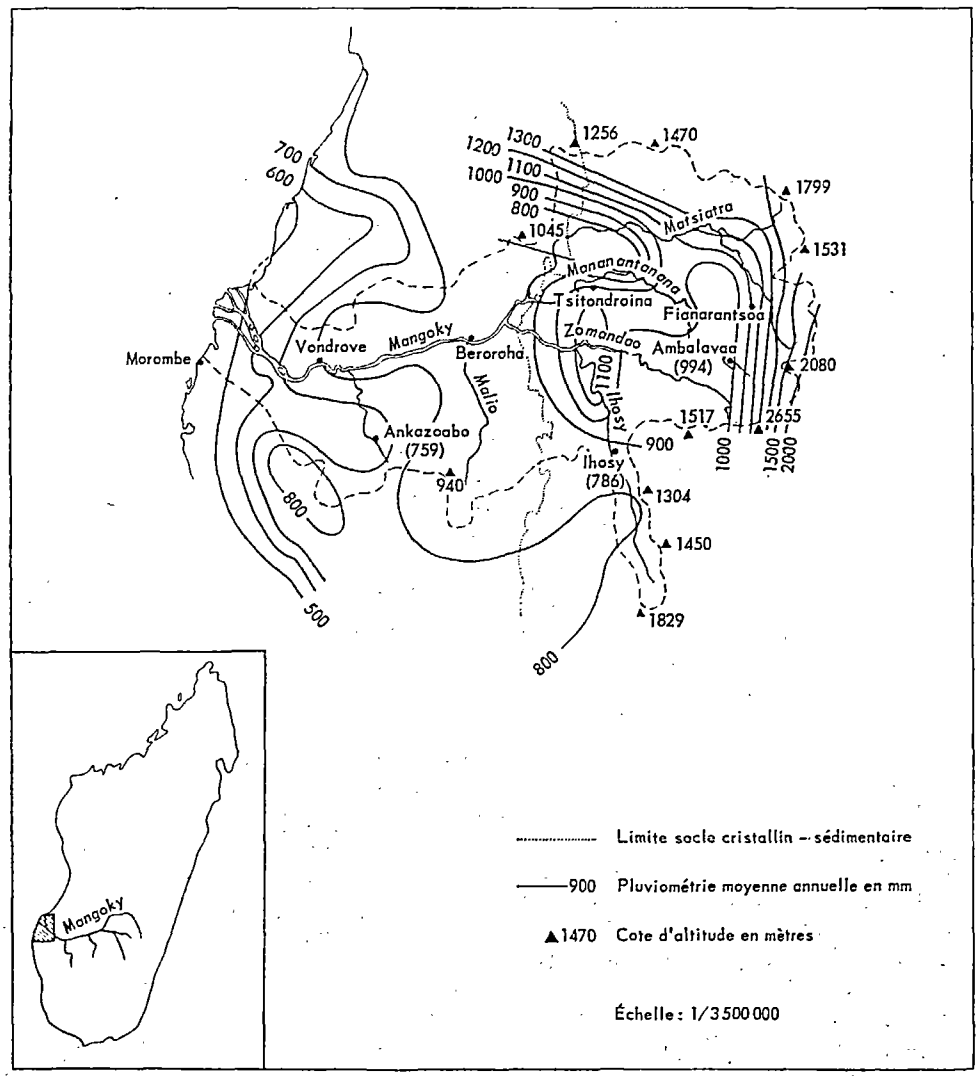


FIG. 1. Situation de la région étudiée et répartition schématique des pluies dans le bassin versant du Mangoky.

faites sur des échantillons répartis dans l'ensemble du delta et de la basse vallée. Certes, pour un même faciès de dépôt ou un même milieu, il existe parfois des variations notables dans les caractéristiques texturales et minéralogiques, mais si l'échantillonnage est fait avec soin on arrive en général à un bon groupement des résultats.

Texture et milieux de sédimentation

Les formations de lit. Elles sont constituées essentiellement par des bancs sableux qui se forment et se déplacent lors des crues importantes et ne subissent que des modifications mineures lors de la décrue par érosion latérale du chenal d'étiage.

La finesse et le degré des sédiments sableux augmentent sensiblement depuis la tête du delta jusqu'aux estuaires principaux (fig. 2) ainsi que les valeurs de la médiane varient entre 0,5 et 0,15 mm en moyenne, l'indice d'hétérométrie (*Hé* de A. Çailleux) entre 0,6 et 0,25, l'indice de triage (*So* de Trask) entre 1,55 et 1,20. Ces bancs sableux peuvent atteindre 1,5 à 2 mètres au-dessus des plus basses eaux; leur partie supérieure est souvent recouverte par une couche de quelques centimètres d'épaisseur d'alluvions fines en plaquettes déposées sous faible épaisseur d'eau lors de la décrue. Ils présentent une stratification oblique et entrecroisée curviligne typique dont chaque unité est de l'ordre de 10 à 20 cm d'épaisseur maximum.

Étant donné la largeur du lit apparent dans la plaine deltaïque (souvent 2 à 3 km) les sables du chenal d'étiage ne diffèrent guère de ceux des bancs de crue que par un triage un peu moins poussé.

Les levées alluviales ou bourrelets de « pré-lit ». Ces levées bordent le lit apparent et présentent une topographie en rides très irrégulières. Il existe le plus souvent une rupture de pente nette entre les bancs de lit et les levées. Ces dernières sont localement érodées en berges concaves.

Les sédiments des levées présentent un faciès « rubané » caractérisé par l'alternance de strates sableuses fines très micacées, à stratification oblique ou entrecroisée, et de strates argilo-limono-sableuses à structure lamellaire ou feuilletée, se délitant en plaquettes. L'épaisseur respective des strates est variable, mais en moyenne ne dépasse guère 20 à 30 cm surtout pour les sédiments fins.

Dans les strates sableuses, les valeurs de la médiane varient le plus souvent entre 0,15 et 0,2 mm avec un indice d'hétérométrie de 0,4 à 0,5 et un indice de triage voisin de 1,4. Dans les strates de sédiments fins, l'allure des courbes granulométriques laisse supposer le mélange de deux fractions distinctes, toutes deux déposées par excès de charge (fig. 3).

La plus grande partie de la fraction la plus grossière de ces strates (limons grossiers et sables très fins) est d'ailleurs constituée par des micas qui contribuent pour beaucoup à la formation des structures lamellaires. En moyenne, la grossièreté des sédiments qui constituent les strates argilo-limono-sableuses fines est de l'ordre de quelques dizaines de microns.

Terrasses inondables et surfaces d'épandage. Les terrasses inondables font transition entre les levées d'une part, les cuvettes de débordement ou les dépressions marginales d'autre part; elles occupent des superficies très importantes dans la moyenne partie de la plaine deltaïque. Les surfaces d'épandage font transition entre

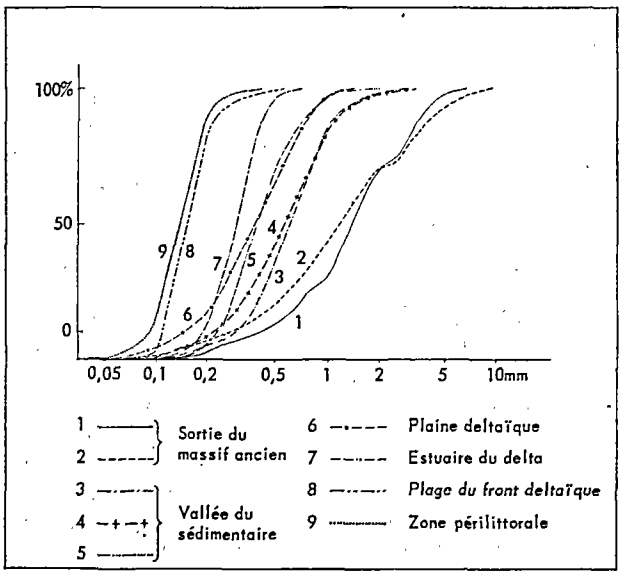


FIG. 2. Exemples de variations de la grossièreté et du triage des sables de lit sur le profil de la basse vallée du Mangoky.

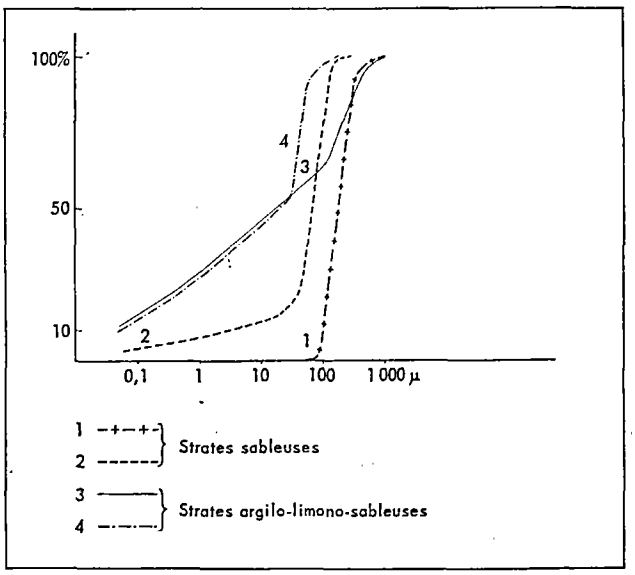


FIG. 3. Sédiments des levées.

la plaine de niveau de base proprement dite et la zone littorale à mangroves.

Ces unités morphologiques sont le plus souvent constituées par des sédiments fins argileux où la fraction argileuse proprement dite inférieure à 2 μ atteint souvent plus de 50 %. Environ 80 % des particules élémentaires ont des dimensions inférieures à 35 μ, le reste étant essentiellement constitué par des micas. En moyenne la grossièreté de ces sédiments est de l'ordre de quelques microns (fig. 4).

Les courbes granulométriques cumulatives semi-logarithmiques présentent un faciès « logarithmique » typique tel que l'a défini A. Rivière en 1952, ou s'en écartent peu. Ces sédiments, évolués par transport fluviatile, ont été déposés par excès de charge sous une épaisseur d'eau relativement faible, le plus souvent inférieure à 1 mètre. Étant donné leur finesse, ils ont un indice d'hétérométrie assez élevé : 2 à 3,5.

Cuvettes de débordement et dépressions marginales

Les cuvettes de débordement plus ou moins fonctionnelles sont inondées par les crues, et l'alluvionnement actuel y est périodique et notable. Dans les dépressions marginales, qui correspondent le plus souvent à des vallées latérales colmatées par le remblaiement récent, l'alluvionnement actuel est faible et des mares y subsistent souvent en saison sèche.

Les sédiments qui constituent ces cuvettes et dépressions sont en général très fins avec des valeurs de la médiane de l'ordre de quelques dixièmes de microns. La fraction argileuse inférieure à 2 μ peut atteindre 70 à 80 % de l'ensemble du sédiment. L'examen des courbes granulométriques permet de déceler un passage fréquent ou une tendance à des faciès très évolués

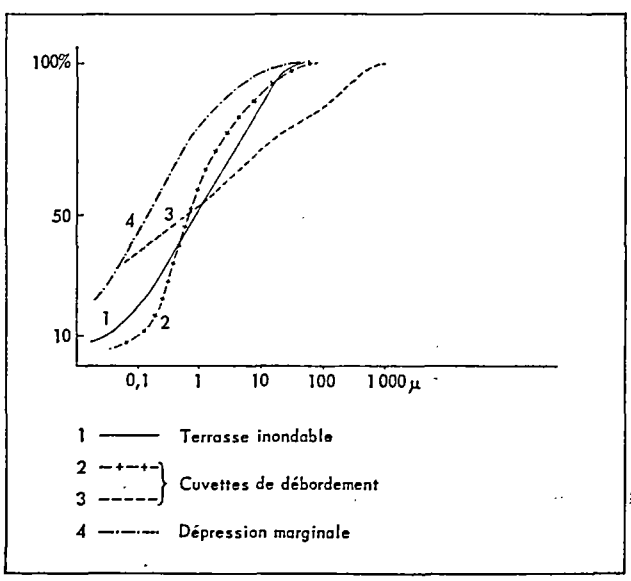


FIG. 4. Sédiments des levées.

(courbes cumulatives semi-logarithmiques convexes vers le haut : faciès « hyperbolique ») qui correspondent à des sédiments déposés par décantation (fig. 4). Ces faciès sont d'autant plus nets que les dépressions sont plus éloignées du lit apparent : les eaux d'inondation ou de ruissellement arrivent dans ces dépressions ayant déjà perdu une grande partie de leur charge et sous des vitesses faibles.

Mangroves anciennes et actuelles. Les mangroves actuelles constituent un front littoral très important sur plus de 60 km. Les dépôts de mangroves anciennes constituent le plus souvent le sous-sol hydromorphe des surfaces d'épandage actuelles.

Bien que ces sédiments soient en général fins, les variations de la grossièreté sont importantes dans le détail en fonction de l'importance des bras d'alimentation. La répartition des chenaux de marée principaux dans le delta étant le plus souvent liée aux systèmes de bras récents ou actuels, il semble que la finesse des sédiments tende à augmenter à mesure qu'on s'éloigne de ces chenaux. En moyenne les valeurs de la médiane varient entre quelques dixièmes de microns et quelques microns, et l'hétérométrie est élevée.

Bien que les courbes granulométriques présentent en général un faciès logarithmique, il n'est pas rare d'observer des tendances au faciès hyperbolique de décantation pour les fractions les plus fines, ou les fractions les plus grossières constituées par des micas.

Dépôts sableux littoraux. Les sédiments sableux d'estuaire se caractérisent par un triage encore plus poussé que celui des sables de la plaine deltaïque : les valeurs de la médiane excèdent rarement 0,3 mm et l'indice d'hétérométrie est le plus souvent inférieur à 0,3. Du fait des remaniements marins ou éoliens on observe fréquemment des distributions bimodales : le premier mode toujours vers 0,3 mm, le second aux environs de 0,16 mm, ce dernier caractérisant assez bien, semble-t-il, les remaniements éoliens récents ou actuels.

En effet, ce second mode est très accusé dans les sables dunaires récents qui dérivent directement des sables dont l'homométrie est déjà très élevée.

Les sédiments du delta immergé. Bien que nous ne disposions actuellement que d'un nombre limité de prélèvements, il semble qu'en fonction de la profondeur et de la distance au rivage actuel, la nature dimensionnelle des sédiments varie de la manière suivante :

A proximité immédiate de la côte, et plus particulièrement au débouché des estuaires les plus importants, des bancs sableux prolongent à faible profondeur (moins d'un mètre) les crêtes prélittorales qui découvrent à marée basse. Il s'agit de sables très fins (médiane voisine de 0,1 mm) et à forte homométrie (fig. 5).

Dans une seconde zone, sous des profondeurs d'eau de l'ordre de quelques mètres, la surface du delta immergé est constituée par des sables vaseux, avec des grossièretés moyennes inférieures au 1/10 mm.

Leur extension varie entre 5 km de large dans la partie septentrionale du delta (la plus active) et 20 km dans sa partie occidentale en régression.

Ensuite, jusqu'aux profondeurs de 20 à 30 mètres, la majorité des dépôts est constituée par des vases où la fraction argile-limon (0 à 20 μ) atteint 40 à 80 % de la masse totale. Au-delà de ces profondeurs, les côtes augmentent très rapidement jusqu'au voisinage de 100 mètres (talus deltaïque) et nos observations dans ce secteur sont encore trop isolées pour conclure.

La plupart de ces sédiments sous-marins sont évolués et ont été déposés par excès de charge : le faciès logarithmique est plus fréquent (fig. 5) avec pour les vases les plus fines une faible tendance au faciès de décantation dans la fraction argileuse inférieure à 2 μ.

Caractères minéralogiques des dépôts récents et actuels

Fraction sableuse. Les sables des sédiments récents sont constitués en forte proportion par du quartz (75 à 95 %), tandis que les feldspaths altérés et ferruginisés ne dépassent guère 10 % et sont souvent inexistants dans les fractions fines de dimensions inférieures à 0,2 mm.

Les teneurs en minéraux lourds sont très variables d'un point à un autre, pouvant aller de 0,5 à 8,5 % de la masse du sédiment, les concentrations les plus élevées se trouvant dans les bancs de lit et les sables de plages.

Les minéraux opaques sont toujours abondants (souvent 30 % des minéraux lourds) avec une proportion élevée d'ilménite. Les minéraux lourds transparents sont caractérisés par l'association grenat-amphibole (hornblende verte), dont les pourcentages numériques cumulés constituent jusqu'a plus de 70 % des minéraux transparents. L'amphibole est généralement nettement dominante. Le cortège des autres minéraux comprend principalement en proportions variables : zircon, tourmaline, disthène, sillimanite, zoïsite, staurotide. Il faut noter également dans les sables très fins la grande abondance de muscovite (10 à 30 % des minéraux transparents) et de biotite plus ou moins chloritisée.

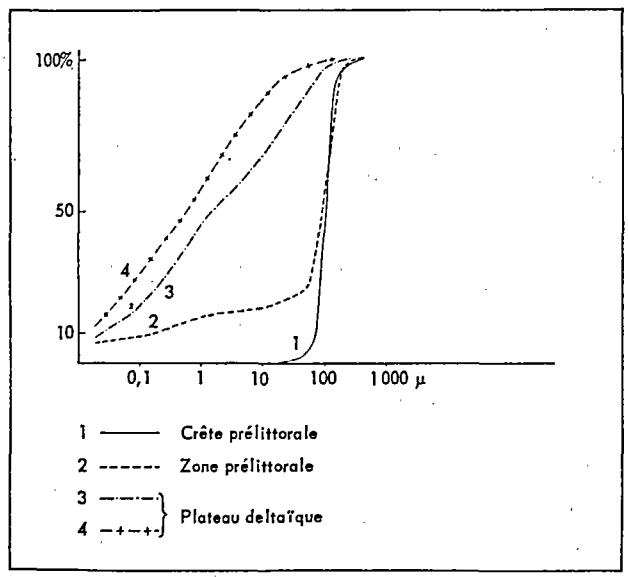


FIG. 5. Sédiments du delta immergé.

Fraction argileuse. Du point de vue de la nature des minéraux argileux, la quasi-totalité des dépôts récents et des sols alluviaux du delta (y compris la surface du delta sous-marin) forment un ensemble homogène : on relève la présence constante de l'association montmorillonite-illite-kaolinite. La montmorillonite (typique à 12 Å) constitue le plus souvent 50 à 60 % environ de la fraction argileuse inférieure à 2 μ. Dans les minéraux à 10 Å la présence de biotite est fréquente. La gibbsite se trouve fréquemment en faibles quantités et on relève également des traces de gœthite.

RELATIONS ENTRE L'ORIGINE DES SÉDIMENTS ET LEURS CARACTÉRISTIQUES TEXTURALES ET MINÉRALOGIQUES

Granulométrie

A la sortie du massif ancien cristallin, on observe que la grossièreté moyenne des sédiments de lit n'excède pratiquement pas 2 mm et que dans la vallée du bassin versant sédimentaire les valeurs de la médiane se fixent rapidement dans un intervalle dimensionnel compris entre 0,65 et 0,30 (fig. 2). Malgré des crues assez fortes mais étalées, à peu de distance du dernier seuil rocheux dans les terrains métamorphiques, le fleuve ne transporte pas de galets, tout au plus des granules (5 mm). Ces faits doivent être imputés à l'importance de la couverture d'altération dans le bassin versant cristallin, où les affluents du Mangoky ne charrient guère en quantités importantes et localement que des galets de quartzites, et surtout au processus géomorphologique. En effet, dans les conditions actuelles, le profil en long de la vallée du sédimentaire a atteint une pente moyenne de 0,75 à 0,8 pour 1 000, pente que le fleuve conserve sur une distance de plus de 200 km, et que l'on peut considérer comme voisine d'une pente d'équilibre, étant donné les conditions hydraudynamiques.

Par ailleurs, les analyses granulométriques des sédiments sableux des rivières affluentes du bassin versant sédimentaire montrent que les valeurs de la médiane varient entre 0,25 et 0,65 mm, c'est-à-dire sont sensiblement analogues à celles observées pour des bancs de crue dans le lit du Mangoky. Par conséquent le fleuve les remanie sans difficulté en améliorant leur triage. Le triage de ces sables du sédimentaire est cependant en général un peu moins bon que celui des sables de la vallée du Mangoky, car ces affluents ont un régime plus irrégulier que celui des affluents des hauts plateaux et un écoulement plus chargé.

Cortège minéralogique des sables

En ce qui concerne la composition minéralogique des dépôts sableux récents et actuels, la prédominance du quartz n'est guère surprenante, étant donné l'altération des roches métamorphiques dans le bassin versant cristallin et l'importance des séries gréseuses à désagrégation facile dans le bassin versant sédimentaire. Cependant le cortège des minéraux lourds porte surtout l'empreinte des apports du cristallin; en effet, à la sortie du cristallin aussi bien que dans la plaine deltaïque, on trouve une forte prédominance de l'association grenat-amphibole : dans les gorges du massif ancien, la hornblende peut constituer jusqu'à près de 70 % des minéraux lourds transparents, dont le pourcentage en poids varie entre 8 et 12 %. Les concentrations sont en général très inférieures dans les sables des rivières du sédimentaire, étant donné l'origine des apports : localement on observe cependant de fortes concentrations en minéraux opaques et en grenat; le cortège minéralogique y présente comme association dominante grenat-zircon-épidote.

Si l'on tient compte des caractères de l'altération des roches et de la pédogénèse (ferrallitisation) dans le bassin versant cristallin, la nette prédominance de l'amphibole et du grenat dans les sédiments du delta est assez surprenante; en effet, en milieu tropical humide ou subhumide, ce sont des minéraux réputés assez facilement altérables (l'amphibole vient en troisième position dans la série de Jackson, avant même la biotite). La biotite est également abondante dans les sédiments du delta; elle est le plus souvent plus ou moins altérée (mica vert). Il faut noter que dans le bassin versant cristallin, plus que les horizons supérieurs rubéfiés des sols ferrallitiques, c'est surtout la couverture d'altération (horizons de « départ ») dont l'épaisseur peut atteindre dans le haut bassin plusieurs dizaines de mètres, qui fournit aux tributaires du Mangoky l'essentiel des matériaux transportés. L'observation courante de cette couverture d'altération *in situ*, dans laquelle la structure de la roche est encore le plus souvent bien visible, permet de constater qu'en général les lits riches en minéraux ferro-magnésiens, bien que libérant des hydroxydes de fer, résistent davantage à l'altération chimique que les lits feldspathiques ou à mica noir rapidement kaolinisés. Ce caractère est d'autant plus net, semble-t-il, qu'on se rapproche de la bordure occidentale des hauts plateaux, là où la pluviométrie annuelle diminue, en même temps que s'accentue le caractère déjà tranché de la saison sèche.

Argiles

La constance de l'association de minéraux argileux observée dans les sédiments du delta semble surtout dépendre de la nature des matériaux qui alimentent la sédimentation. En effet, un certain nombre de considérations laisse supposer ici la prédominance de l' « héritage » pour reprendre une expression déjà utilisée par Millot, 1952; Rivière et Visse, 1954; Nesteroff et Sabatier, 1962; autrement dit l'influence des roches mères du bassin versant et des conditions qui président à leur désagrégation.

L'analyse roentgenographique des fractions argileuses des débits solides du Mangoky prélevés à la sortie du massif cristallin a montré que la quasi-totalité de la kaolinite trouvée dans les sédiments récents provient du bassin versant cristallin. Il en est sans doute de même pour les minéraux à 10 Å du type illite ou micas qui dans ces débits solides sont en association avec la kaolinite, mais en plus faibles quantités. La montmorillonite y est absente ou seulement à l'état de traces.

Par contre, dès le début de la vallée dans les terrains sédimentaires, c'est-à-dire dans la dépression périphérique du massif ancien, ce minéral fait son apparition dans les sédiments récents et son importance croît rapidement pour atteindre dans les gorges du sédimentaire les proportions trouvées dans les sédiments du delta, soit environ 50 à 60 % de la fraction argileuse inférieure à 2 μ.

L'examen des débits solides du fleuve à la sortie des gorges du sédimentaire, en tête de la plaine deltaïque, confirme ces résultats; et nous avons vu que la même association des minéraux argileux se retrouve dans les dépôts récents du delta sous-marin.

L'analyse des roches mères du bassin versant sédimentaire, en particulier des séries stratigraphiques marno-calcaires, pour déterminer la composition de leur fraction argileuse, est en cours; mais dès maintenant, du fait des lieux et de la densité des prélèvements d'alluvions récentes le long du profil en long du Mangoky, on peut dire qu'il est très probable que les apports détritiques en provenance du sédimentaire sont la principale source de la montmorillonite trouvée dans les sédiments récents de la basse vallée et du delta. De plus, on observe que pour les principaux affluents du bassin versant sédimentaire, les dépôts argileux récents contiennent en général une association montmorillonite-kaolinite où le premier minéral est nettement dominant avec des proportions pouvant atteindre 80 % de la fraction argileuse.

Cependant, la formation de montmorillonite par « néogénèse » dans les sols du delta n'est pas complètement à écarter : en effet, on relève localement des proportions très élevées de ce minéral (70 à 90 % de la fraction inférieure à 2 μ). Il s'agit le plus souvent d'horizons gypso-sodiques de sols à hydromorphie temporaire ou d'horizons de gley de sols marécageux salés et à alcalis; il semble que dans ces sols déjà plus ou moins évolués le milieu fortement alcalin ait favorisé l'augmentation du taux de montmorillonite. Par contre, dans les dépôts très récents, même en milieu hydromorphe basique (sous-sol de mangroves en particulier), les proportions de minéraux argileux sont à peu près les mêmes que dans la majorité des sédiments du delta.

Par ailleurs, il semble que les quantités faibles à très faibles d'hydroxydes de fer et d'alumine observées dans les sédiments récents soient dues surtout au fait que dans le bassin versant cristallin, l'altération des roches métamorphiques dans les zones de « départ » (couverture d'altération proprement dite) se limite souvent au stade kaolinique. Même dans les horizons supérieurs des sols ferrallitiques, les hydroxydes de fer et d'alumine, quoique abondants, sont souvent mal cristallisés (d'après les quelques résultats que nous possédons, la présence en quantité notables de gibbsite et de goethite dans les alluvions récentes du versant oriental perhumide de l'île semble beaucoup plus fréquente que sur la côte ouest).

INFLUENCE DES CARACTÉRISTIQUES TEXTURALES ET MINÉRALOGIQUES DE LA SÉDIMENTATION RÉCENTE SUR LES PROPRIÉTÉS PHYSICO-CHIMIQUES ET L'ÉVOLUTION DES SOLS ALLUVIAUX

Texture et classification

Les sols du delta peuvent être classés en cinq groupes principaux : *a*) sols minéraux bruts; *b*) sols peu évolués d'apport; *c*) vertisols hydromorphes; *d*) sols hydromorphes moyennement ou peu humifères à gley; *e*) sols salins.

Dans les prospections à grande échelle (1/10 000) faites dans le delta pour la mise en valeur, la texture a été un critère important de différenciation pour les sols peu évolués, en tenant compte du milieu de sédimentation et des changements intervenus dans celui-ci (recouvrements, sols à profil complexe). Les catégories suivantes ont été distinguées : sols sableux (anciens bras); sols sablo-limoneux à limono-sableux avec présence fréquente de « couches-drains » sableuses (levées alluviales et surfaces d'épandage); sols de recouvrements limono-argileux à argilo-sableux sur sables (axes de drainage ou ancien bras colmatés); sols limono-sableux à limono-argileux stratifiés (levées alluviales); sols limoneux (terrasses inondables); sols limono-argileux (cuvettes de débordement récentes); sols à recouvrements limono-sableux sur sous-sol argileux (axes de drainage récents sur l'emplacement d'anciennes cuvettes); sols argileux (cuvettes de débordement stabilisées plus ou moins anciennes).

Ces catégories sont basées essentiellement sur une appréciation de terrain, laquelle ne correspond pas toujours étroitement avec les résultats de l'analyse granulométrique qui sont assez variables dans le détail. En fait, si on reporte sur un diagramme triangulaire par exemple un certain nombre de résultats concernant les horizons caractéristiques des différents sols alluviaux récents, on constate rapidement que les points se groupent selon trois zones principales (fig. 6) qui correspondent aux milieux de sédimentation caractéristiques du complexe deltaïque : levées alluviales, terrasses inondables et surfaces d'épandage, cuvettes de débordement. Toutefois les dépôts fluvio-marins de mangroves présentent une plus grande dispersion, car ce milieu est autant conditionné par les facteurs biologiques que par les facteurs hydrodynamiques : les racines de palétuviers constituent un filtre très actif pour les eaux de crues chargées et le triage est moins net que dans les zones où les conditions d'écoulement sont moins gênées par la végétation. Aussi, en fonction des apports, il existe des vases de mangrove relativement grossières, contenant 20 à 60 % de sables, et cela a été également observé dans d'autres deltas de la côte ouest malgache.

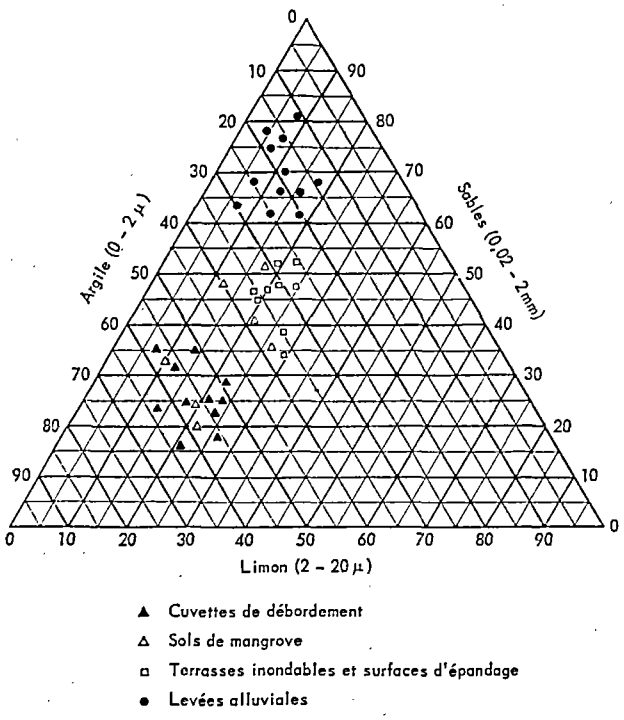


FIG. 6. Plaine deltaïque du Mangoky.

Stabilité structurale

Les tableaux 1 et 2 montrent quelques résultats obtenus pour les valeurs de la vitesse de filtration au laboratoire et de l'indice d'instabilité structurale (méthode Henin, 1958) en fonction des teneurs en éléments inférieurs à 20 μ et en sables fins. Les teneurs en matière organique interviennent en général peu dans la stabilité structurale, par suite des faibles pourcentages d'humification. Aussi, l'instabilité a tendance à augmenter avec la fraction argile-limon, et la vitesse de filtration à diminuer. Il faut noter que la perméabilité est rarement élevée (valeurs de K le plus souvent inférieures à 2,5 cm/*h*); en effet, dans les sols sableux le faible pourcentage des sables grossiers et l'abondance des micas dans les sables fins diminuent la perméabilité; dans les sols

TABLEAU 1. Horizons de surface.

Argile (0-2)	Argile + limon (0-20)	Sable fin	Matière organique	Humus / Mat. organ.	K	Indice de stabilité
%	%	%	%		cm/h	
11,2	20,0	77,4	1,5	14	1,9	0,37
11,2	20,8	73,2	2,0	5	1,7	2,91
20	35,8	52,7	2,9	7	2,2	0,67
25,4	47,6	48,3	1,3	6	2,0	1,74
30,5	46,4	29,9	4,0	12	2,0	0,62
34,2	53,2	41,0	3,8	4	1,0	3,93
35,9	54,8	40,3	1,6	7	1,4	3,15
41,8	69,6	21,6	4,6	8	4,2	0,71
47,4	65,2	23,9	4,6	21	1,2	0,7
49,2	71,2	22,9	1,5	10	0,5	7,1
53,3	76,4	16,6	2,5	12	0,7	2,9

TABLEAU 2. Sous-sol.

Argile (0-2)	Argile + limon (0-20)	Sable fin	Matière organique	K	Indice de stabilité
%	%	%	%	cm/h	
11,2	16,6	47,8	0,7	1,1	1,1
10,0	22,0	68,8	0,3	1,1	1,1
12,8	22,0	76,2	1,2	1,1	1,6
17,2	22,0	73,3	0,7	2,3	4,7
28,2	46,4	56,4	1,3	2,5	2,2
31,9	54,0	43,4	1,2	0,1	2,6
35,0	52,0	40,1	0,7	0,5	2,8
39,2	61,6	29,4	1,2	1,4	1,4
43,8	63,0	29,2	0,8	1,2	11,7
43,4	75,6	19,5	1,3	1,7	1,5
40,1	55,2	29,6	1,3	0	6,5
51,0	64,4	25,1	1,0	0,9	2,1

TABLEAU 3.

Type de sol	Agrégats grossiers		
	Alcool	Air	Benzène
	%	%	%
Sols sablo-limoneux à limono-sableux de levées	48 - 55	30 - 44	16 - 41
Sols limoneux à limono-argileux de terrasses récentes	28 - 38	9 - 11	4 - 6
Sols argileux de cuvettes	34 - 55	9 - 22	5 - 6

argileux elle est modifiée par la présence fréquente et notable de sodium dans le complexe.

D'ailleurs la plupart des sols alluviaux peu évolués se caractérisent par une fraction agrégée stable, après prétraitement au benzène ou sans prétraitement, moyenne à faible, très faible dans sols à argiles sodiques (pourcentage d'agrégats supérieurs à 200 μ).

On peut donc dire qu'en moyenne les sols alluviaux du bas Mangoky sont assez sensibles à l'action de l'eau et ont une structure peu stable. Aussi, étant donné la longueur de la saison sèche et, pendant cette saison, l'absence quasi totale de couvert herbacé sur les sols cultivés, l'agressivité et l'irrégularité des premières pluies, la minéralisation rapide de la matière organique, et la texture due à l'origine alluviale des matériaux originels, deux facteurs sont essentiels pour la mise en valeur de ces sols : le maintien d'un taux minimum de matières organiques humifiées d'une part, la préparation culturale d'autre part (intérêt de la pré-irrigation).

Aptitude à l'irrigation

Les mesures de perméabilité en place (infiltromètre à cylindres) ont montré que l'infiltration de l'eau dans un horizon texturalement homogène obéit à la relation générale : $D = Ct^n$ (D : quantité infiltrée en fonction du temps t); C (constante exprimée en centimètres cubes) permet dans une certaine mesure d'apprécier la mouillabilité du sol au début de l'expérience. L'exposant n, le plus souvent compris entre 0 et 1, est d'autant plus faible que la quantité d'eau infiltrée diminue en fonction du temps (colmatage).

Dans les sols alluviaux peu évolués la perméabilité en place a varié entre 1.10^{-4} m/s dans les sols légers et 1.10^{-6} dans les sols les plus argileux et peu structurés. Les valeurs de C ont varié entre 11 et 150, celles de n entre 0,31 et 0,93.

Selon les types texturaux, la quantité d'eau disponible (ou réserve en eau du sol) sur les 75 premiers centimètres d'un sol relativement homogène du point de vue des apports alluviaux, varie entre 35 et 100 mm (à l'exclusion des sols très sableux des anciens bras). Pour la culture irriguée du coton, ces valeurs conduisent à des doses théoriques d'arrosage variant, selon la période de végétation, entre 150 et 650 m³/ha pour les sols légers, entre 350 et 1 800 m³/ha pour les sols les plus lourds, compte tenu des conditions suivantes : irrigation du 15 décembre au 15 mai; déficit théorique pendant cette période, 376 mm; consommation effective par hectare, 7 500 m³; coefficient d'efficience, 50 %.

Propriétés chimiques et fertilité naturelle

Étant donné le faible taux d'humification de la matière organique même dans les sols marécageux, les proportions d'éléments fins influent beaucoup sur le complexe absorbant et leurs réserves minérales. Ainsi la capacité d'échange sur un large intervalle est d'assez près directement proportionnelle à la teneur en argile : sa valeur passe de 15 à 20 milliéquivalents pour 100 g dans les sols contenant 15 à 20 % d'argile, à 40 ou 45 milliéqui-

valents pour 100 g dans les sols contenant 55 % d'argile. Les valeurs sont encore plus élevées si les teneurs en matière organique sont supérieures à 3 ou 4 % pour les sols argileux.

La réaction du sol est le plus souvent neutre. En grande majorité les sédiments ne sont pas calcaires; le calcaire ne se dépose que localement dans les sols argileux de cuvettes en taches ou nodules d'hydromorphie temporaire et dans ce cas est souvent associé à des cristallisations plus ou moins denses de gypse (sols argileux un peu évolués de cuvettes stabilisées, vertisols hydromorphes).

Du fait de nappes assez minéralisées, de la nature des argiles, de la saison sèche marquée, le complexe absorbant des sols est le plus souvent très richement pourvu en éléments échangeables, en particulier en calcium et magnésium. Les sols salins sont souvent à alcalis, mais leur structure en est rarement modifiée (sols jeunes, salure par la nappe littorale). Dans les dépôts de mangroves, le rapport Na/T peut atteindre 50 % et le rapport Mg/Ca est fréquemment supérieur à 1.

Les réserves minérales sont également abondantes dans presque tous les sols par suite de la présence dans la fraction limoneuse de nombreuses espèces minérales en voie d'altération (en particulier biotite et amphibole).

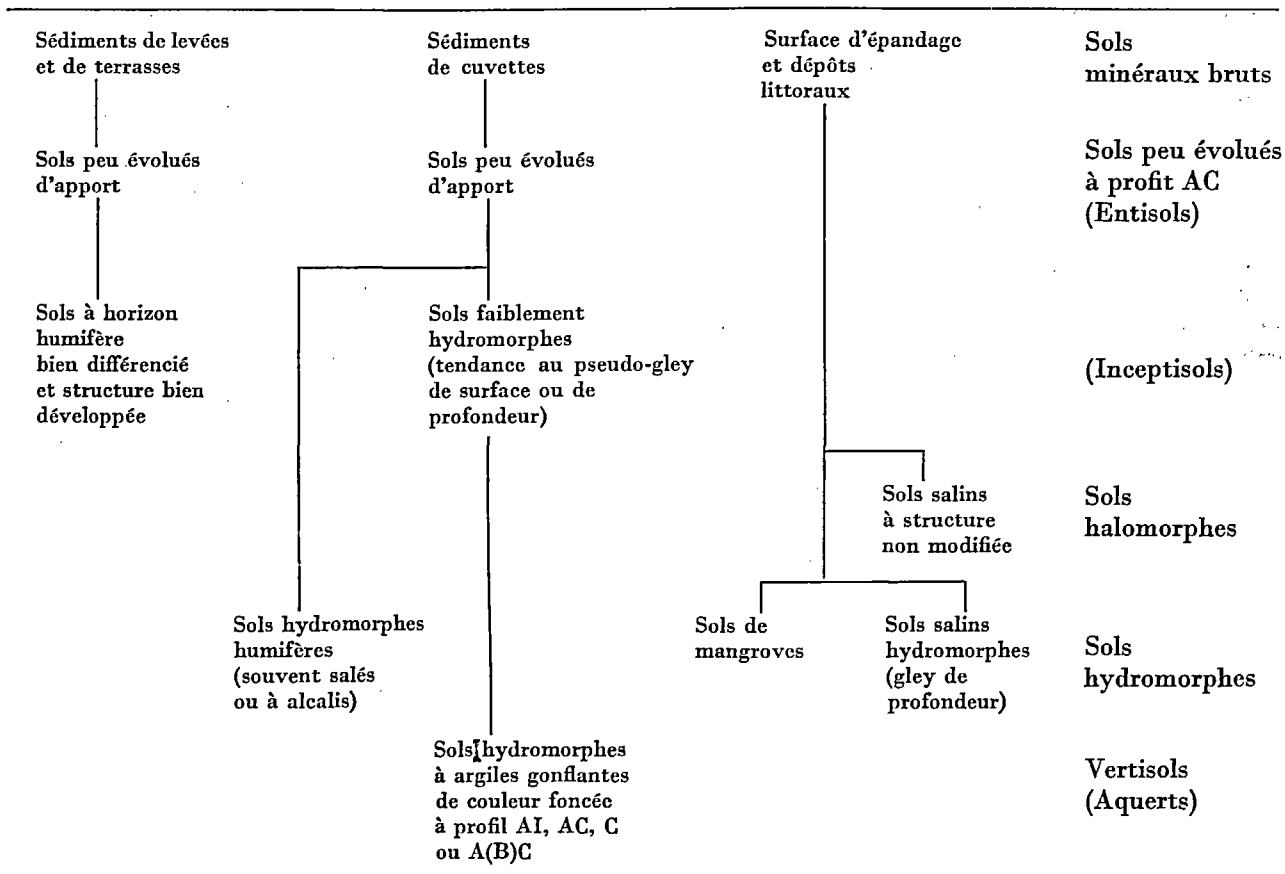
Évolution des sols

L'influence de la texture et de la composition minéralogique (en particulier des argiles) des dépôts alluviaux, liée aux actions conjuguées du milieu originel de sédimentation, de la morphologie actuelle et des facteurs climatiques (saison sèche marquée), est très importante dans l'évolution des sols du delta.

On peut représenter schématiquement les principaux stades d'évolution des dépôts alluviaux (ci-dessous).

D'après ce schéma on peut voir que c'est surtout dans les matériaux fluviatiles fins et argileux que la différenciation pédogénétique est la plus poussée, en particulier, pour des raisons de drainage. En effet, un drainage plus ou moins défectueux en saison des pluies, une dessiccation de longue durée en saison sèche sont à l'origine de cristallisations salines (de gypse surtout), le plus souvent très disséminées dans le profil, de taches calcaires, de marmorisation, dans de rares cas de concrétions ferro-manganésifères.

Ces mêmes conditions, liées à la nature des colloïdes argileux et à un fort pourcentage de sodium sur le complexe absorbant, favorisent évidemment la formation de vertisols hydromorphes qui présentent le plus souvent une accumulation dispersée gypso-calcaire en taches ou en cavités.



Un mauvais drainage permanent en profondeur (nappe littorale surtout) a pour conséquence la formation d'horizons de gley caractéristiques.

Enfin, si le sol est inondé d'une manière quasi permanente, il s'établit une végétation marécageuse (en particulier peuplements à *Typha angustifolia*) avec formation d'un horizon organo-minéral plus ou moins consistant.

Par contre, dans les sols bien drainés, l'évolution pédogénétique est principalement liée à la permanence suffisamment prolongée d'un couvert végétal dense (forêt d'alluvions ou prairie de hautes graminées) : ce cas est relativement peu fréquent à cause des importantes destructions faites par l'homme. En présence de sels, étant donné les importantes variations du niveau de la nappe dans ces sols perméables, il n'y a pas d'accumulation localisée. Cependant dans la zone littorale, les sols sableux sont souvent recouverts d'une mince croûte saline en saison sèche avec une végétation clairsemée à base de salicornes (nappe fluvio-marine à faible profondeur).

Summary

On the textural and mineralogical characteristics of recent sediments and alluvial deposits in the delta of the River Mangoky (south-western Madagascar) (J. Hervieu)

The delta of the Mangoky, which lies in the south-western part of the island in a dry tropical area, covers approximately 570 square miles. Its sloping basin spreads over 22,780 square miles of the old metamorphic shelf and its silt covering, going from a dry tropical climate to the sub-humid to humid tropical climate of the High Plateaux of Madagascar.

Textural analysis of the fluviatile silt has made it possible to determine, according to the amounts and size of the particles and the *facies* of the deposit, a certain number of sedimentation areas such as sandbars, alluvial levees, flood-prone terraces and dissipating areas, overflow basins and marginal depressions, past and present mangrove swamps, littoral deposits, continental shelf, etc.

The heavy transparent minerals in the sand are characterized by the distinct predominance of the amphibole-garnet-white mica association.

In the clayey portions, the montmorillonite (50 to 60 per cent on the average) - kaolinite-illite association is constantly present.

The origin of the silt largely explains the textural and mineralogical characteristics of the recent deposits which, for the most part, are "inherited". The geomorphological development of the lower valley, the characteristics of the greater or lesser ferrallitic alteration in the sloping crystalline basin and the petrographic nature of the rocks of the sedimentary slope of the basin are the main factors which, together with climatic and hydrological factors, condition the different aspects of recent and present sedimentation.

The textural and mineralogical characteristics of recent silt deposits have a preponderant influence on the physical and chemical properties of the delta soils and on their potential for cultivation. From the point of view of soil development, it is primarily in the fine clayey substances that the pedogenetic differentiation is greatest, particularly on account of drainage.

Soils of East Pakistan

M. Amirul Islam

Studies of tropical soils have been concentrated mainly on latosols, black clays (Regur soils) and volcanic ash soils. Relatively less attention has been paid to alluvial soils. Yet these are the soils which carry the bulk of the population living in the tropics. In South-East Asia some of the highest densities of population in the world are found on these soils. The problems of still further increasing food production from these soils are amongst the most urgent facing mankind today. These problems are clearly observed in East Pakistan. Some information on the soils of East Pakistan is presented here as sample material.

For about half a century, quite a substantial amount of work has been conducted in this region, mainly for assessing fertility status and also for solving some fundamental problems. But this knowledge was not enough for making an inventory of the soil resources of the country and for making a classification of soil units. For the last twenty years, soil survey has been progressing rather slowly but we are now in the process of starting soil survey on a bigger scale with assistance from the United Nations Special Fund. Pending the availability of more detailed information, I shall try to present here a very short, generalized résumé of the available information and no attempt will be made to give detailed descriptions of soil series and soil profiles.

On the basis of parent materials, rather than on the present-day processes of profile development, we used to classify the soils of East Pakistan into seven distinctive soil tracts. Broadly these can be grouped into three physiographic divisions: hill soils, old alluvial soils, and recent alluvial soils.

Hill soils occupy the hills of Chittagong, Chittagong hill tracts, low hills and hillocks of Sylhet, Garo hillocks in the Netrokona sub-division of Mymensingh district and Lalmai hills of Comilla district.They are composed of the Tertiary rocks and unconsolidated Tertiary and Pleistocene sediments. Sufficient investigation has not been carried out on these soils. Valley soils of the hilly tract are quite fertile and are highly valued for paddy cultivation. Most of the hills are under forest. A substantial part of the Chittagong hill tracts is under *jhum* or shifting agriculture practised by primitive tribal people.

Old alluvial soils include the tracts of Madhupur and Barind. The Madhupur tract covers an area about 70 miles long and 35 miles wide. It includes the northern part of the Sadar sub-division of the Dacca district, the eastern part of the Tangail sub-division and the south-western part of the Sadar sub-division of the Mymensingh district. The Barind tract in East Pakistan covers about 2,800 square miles. It includes the Sadar sub-division of the Dinajpur district, a portion of the Bogra district on the western side of the River Korotoa, and the Natore, Naogaon and Nawabganj sub-divisions of the Rajshahi district.

The soils of these two tracts have been formed on the old alluvium of the Pleistocene period. They stand on high land tracts above flood level, intersected by numerous gentle depressions. They belong to the latosol group of genetic soils. They are clayey in texture, reddish to yellowish in colour, contain numerous ferruginous concretions, are relatively rich in iron and aluminium, are highly aggregated, and have a high phosphate-fixing capacity. The pH varies from 6 to 6.5. They are deficient in nitrogen, phosphorus, potassium and lime. They have deep mottled sub-stratum. The soils of Madhupur tract contain 20 per cent illite, 5 to 20 per cent vermiculite and 60 per cent kaolinite. The presence of 2 : 1 type of clay minerals indicates that these soils are relatively young latosols. [1]

Recent alluvial soils are found in the Gangetic alluvium, Tista silt, Brahmaputra alluvium and coastal saline tracts. It may be emphasized here that the recent alluviums are the most important soils of East Pakistan.

1. See: H. Brammer. An outline of geology and geomorphology of East Pakistan in relation to soil developement, 1963 (unpublished).

1. Gangetic alluvium has been formed by the deposits of the Ganges and many of its tributaries, and has been classified as river landscape soil. These soils are mostly rich in calcium, magnesium and potassium. They also contain free calcium carbonate which is important in controlling their physical properties. These soils are characterized by nitrogen and phosphate deficiency and locally by a strong to very strong alkalinity. Fine sandy to silty loams which are grey in colour without any profile development predominate. The pH varies from 7 to 8.5. This tract can be further sub-divided into: (a) the moribund Gangetic delta and (b) the active Gangetic delta (Nafis Ahmad, 1958).
   (a) The western part of the Ganges delta has been abandoned by active tributaries of the river. Many former tributaries have been silted up in their upper reaches and the areas in the moribund delta are no longer receiving fresh alluvium from the Ganges. This area includes Kushtia, Jessore, west Faridpur and north-west Khulna.
   (b) The active Gangetic delta is situated along the present course of the River Padma which ultimately joins with the Brahmaputra, Meghna, etc. It includes parts of the Rajshahi, Pabna, Faridpur, Dacca and Bakerganj districts.
2. In the Tista silt tract the alluvium has been deposited by the River Tista which has shifted its course eastward during the last 200 years. It occupies the whole of North Bengal, except the area covered by the Barind tract. These soils are sandy to sandy loam in texture, without any profile development, light grey in colour, poor in lime and respond to N.P.K. fertilizers. The pH ranges from 6 to 6.5.
3. The soils in the Brahmaputra alluvium tract include samples of all the fully inundated areas in the region of active rivers. Since the Brahmaputra, before taking its present course about 100 years ago, used to flow on the eastern side of the Madhupur tract and because the Tista and the Ganges join this river before reaching the sea, all the lands inundated by the Padma, Brahmaputra, Meghna and their tributaries in the districts of Mymensingh, Dacca, Sylhet, Comilla, Noakhali and Chittagong have been included under Brahmaputra alluvium.

   The soils of this tract are replenished every year by fresh deposits of silt carried down by flood-water and because of this are fertile and rich. The texture varies from place to place, and the soils are grey in colour without developed profiles, but with stratification of alluvial deposits. Almost all kinds of crops are grown of which jute and paddy are the most important ones. The pH varies from 5.5 to 6.8.
4. The coastal saline tract is a part of the active flood-plain, but is subject to flooding with saline water at high tides. It includes the southern parts of Khulna and Bakerganj districts and the islands and coastal areas of Noakhali and Chittagong districts. The famous Sundarbans near the Bay of Bengal are a part of this saline tract. In the Sundarbans, and along the creeks elsewhere, mangrove forest vegetation prevails. *Aman* paddy is cultivated in other areas of this tract where monsoon rains or floods are sufficient to wash down the salt from the surface soil (Brammer, 1963, see footnote on page 83). Most soils appear to be developed in fine-textured tidal deposits. Peat and organic layers occur in some basin sites. Even where protected from tidal inundation by embankments the basin soils become saline during the dry season due to the upward movement of salt from a saline water table.

   Some soils contain large amounts of sulphide in their profile and are liable to become extremely acid if artificially drained. These areas may formerly have carried swamp vegetation which has subsequently been cleared to provide cultivable land. Newly colonized areas along the Chittagong coast provide such a problem. Sulphides are liable to occur in significant amounts in the tidal muds of the Sundarbans.
5. Other lands under active flood-plains include (a) *chars* and (b) *beels*.
   (a) The new formations of lands called *chars* are a characteristic feature of the region of active rivers of East Pakistan. The braided channels of the rivers, the meandering and shifting of river courses give rise to the formations of *chars*. This new land is often very extensive and the locality of its formation can never be anticipated. Some of the *chars* often disappear as quickly as they come up and others may consolidate into densely populated islands (Nafis Ahmad, 1958). The *chars* thus formed consist of fertile soil and soon after can take on crops like paddy, water-melons, etc. They play an important part in the economy of the flood-plain.
   (b) Another important characteristic of the flood-plains of the active rivers is the occurrence of basin-shaped areas locally called *beels* and *haors*. Though for the greater part of the year they remain under water and could be regarded as lakes or water areas, the soils of these areas cannot be left out of consideration because of the fact that at some time of the year they do dry up and the land is then used for growing crops, particularly paddy.

   The *beels* are usually scars and ox-bow lakes or back-lands of old river beds, but tectonic subsidence is also regarded as one of the causes of the origin of these basins. Large numbers of such *beels* are scattered all over East Pakistan. The biggest ones are the Chalan *beel* on the border of Rajshahi and Pabna districts, the Gopalganj *beel* in the Faridpur district, and the *haors* of Mymensingh, Sylhet and Comilla in the Sylhet basin.

   The major part of the Sylhet basin proper is

a low-lying area subject to deep flooding (10 to 20 ft.) during the monsoon season. Except for some coarser materials on the fringes, the most extensive soils of this area are fine-textured. Peat layers occur in some soils. Most of the soils appear to be medium acid but organic soils are strongly acid. Recent studies indicate that the soils associated with the slightly older alluvium have well-developed profiles. There is typically a weakly to moderately developed B horizon with prismatic and angular blocky structure with a clay coating or clay-humus coatings present on the faces (Brammer, 1963, see footnote on page 83).

FERTILITY OF EAST PAKISTAN SOILS

The latosol groups of soil are generally poor in plant nutrients, but they have been found to make good response to improved agricultural practices. Good yield of certain crops such as sugar-cane, paddy and vegetables can be obtained by the liberal application of fertilizers together with a regular water supply. Their elevated positions make crops secure from the hazards of flood. They are also suitable for fruit orchards. One can find extensive orchards of "jack fruits" on the Madhupur tract of East Pakistan.

The recent alluvial soils are regarded as fertile soils, but in comparison with other regions of the world the yield of crops in East Pakistan is rather poor. The yields of sugar-cane and paddy are amongst the poorest in the world. The climatic hazards, either too little or too much water at a time, and unimproved cultivation practices may be responsible for poor yields. But the fact that even without much improvement in other agricultural practices the application of fertilizers alone can increase the yield of paddy by 50 to 100 per cent and of sugar-cane by more than 100 per cent indicates that these alluvial soils of East Pakistan are rather poor in plant nutrients. Most of the soils show response to the application of nitrogenous and phosphatic fertilizers. The old alluvial soils and the sandy soils of the Tista silt tract need potassium in addition (Islam, 1961). With all the disastrous effects of inundation, the soils of the flood-plains of the active rivers are the most important soils of East Pakistan.

PROBLEMS OF EAST PAKISTAN SOILS

One of the most important characteristics of the recent alluvial soils, particularly those in the flood-plains of the active rivers, is their state of submergence. They remain fully under water, sometimes from 10 to 12 ft. deep or even more, from June to September. The wet condition actually begins in May and continues up to the end of October. This submergence initiates a chain of both physical and chemical reactions which pronouncedly change the soil properties and materially alter the soil behaviour and land-use pattern.

Among the physical effects of flooding and puddling by implements are changes in such properties as structure, permeability, cohesion, plasticity, consistence and gaseous exchange between the soil and the air. The most important chemical effect of submergence is the change of redox potential, i.e., a reduction of oxidation reduction potential. The general consequence of such a change is that the oxidized constituents such as Fe^{+++}, Mn^{++++}, NO_3' and SO_4'' ions that characterize a well-drained soil virtually disappear and their places are taken by their reduced counterparts, Fe^{++}, Mn^{++}, NH_4^+ and S'' ions (Islam, 1959). The ferrous iron can take part in base exchange reaction and displace Na, K, Ca, Mg, etc., from exchange complex. Under conditions of good drainage and flow of water across the field, these elements can be lost and the field is left with, so to say, washed and clean soil. This may be one of the reasons for the poor productivity of the otherwise fertile alluvial deposits of East Pakistan.

It has been found that by waterlogging the soil the concentration of ferrous iron increases together with simultaneous increase of 0.5 N acetic acid soluble phosphorus (Islam and Elahi, 1954). This reduction of iron and solubility of phosphorus increases by the incorporation of easily decomposable organic matter. This is also the reason why wet-land paddy (*aman*) in many cases does not respond to the application of phosphatic fertilizers though the upland crops or dry-land paddy (*aus*) in the same land make good response. Nowadays it is being gradually realized that the conventional methods of determining available nutrients by analysing air-dry soils cannot be applicable to paddy fields under submerged conditions. For the purposes of assessing the fertility status of paddy fields under submerged conditions, analysis of unoxidized soil seems more appropriate. It will, of course, involve developing suitable sampling techniques, methods of analysis and establishing correlation between fertilizer application and crop response.

Very few crops can thrive under such reduced and submerged conditions with poor nutrient contents. Rice seedling does well to thrive under such unfavourable circumstances. Though not an aquatic plant, it has the wonderful acquisition of amphibian character (Mitsui, 1954). It possesses two adaptive mechanisms which enable it to thrive in a submerged soil: a highly developed system of an aerobic respiration in the early phase and the transport of oxygen from shoot to root in the later stage.

In spite of this unique character of the paddy plant, it has been found that prolonged submergence adversely affects the roots, through the production of toxic organic acids in soils of high organic matter content and draining off the water to produce oxidative condition in the root zone at the appropriate stage is essential for proper growth (Mukerjee, 1962).

But under the conditions prevailing in East Pakistan,

the most important and extensive paddy crop, the *aman* paddy, is grown during the rainy season. The possibility of creating any oxidative condition is unthinkable when submergence and a high level of flooding is the normal condition. However, the creation of ideal soil conditions for the cultivation of paddy and other cash crops is possible by providing irrigation water during the dry season, when a long spell of drought prevails from December to April. It can be said to the credit of the East Pakistan Water and Power Development Authority that it has taken up a number of irrigation projects for supplying irrigation water during the dry season.

Another important project carried out by this Authority and aimed at improving the soil condition for crop production is the coastal embankment project, which has undertaken the construction of 2,800 miles of embankment and 73 project areas (called polders). This project proposes to protect 3.4 million gross acres from periodic tidal inundation during high tides and from monsoon floods during the rainy season (EPWPDA, 1961). The construction of embankments might give rise to additional problems, one of which is the salinity and waterlogging due to an increase in the ground-water table elevation. The embankments along the polders will no longer allow the tidal deposits of marine sediments. Sediments deposited outside the polders will convert these into basin-shaped areas and will create drainage problems. Another important problem likely to occur is the production of toxic substances in areas which are rich in organic matter especially of mangrove swamp origin. It has been found that, when a land is reclaimed by constructing high embankments completely encircling the land, a soil disease locally known as *kosh* appears as an aftermath of land reclamation. In the Chittagong coastal area it has been found that large areas of reclaimed land have gone out of production due to the appearance of *kosh* thus defeating the very purpose of reclamation (Islam, 1955).

The *kosh* soils are characterized by :

1. Occurrence of high amounts of chloride and sulphate in the subsoil, semi-decomposed organic matter, soluble iron and aluminium salt content in large amounts.
2. Prevalence of high water table resulting in reducing condition.
3. Presence of free hydrochloric and sulphuric acid in the soil, thereby producing an extremely high acid condition in the soil.
5. Salt afflorescence during the dry season which raises the salt concentration of the surface soil beyond the tolerance capacity of crops.
5. The seepage of sea-water into subsoil during high tides.

These *kosh* soils of East Pakistan appear to be the same as the cat-clays or acid sulphate soils of the tropics as described by Moormann (1963).

For the present, these problems are regarded as of minor importance compared to the benefits to be derived from the embankments. However, due importance should be given to their investigation and solution before they assume menacing proportions.

Research achievements on the soils of temperate regions have been phenomenal, but our soil problems are quite different. Therefore, great achievements in temperate regions offer only limited help to the solution of problems peculiar to humid tropical deltaic areas.

Appearance and disappearance of islands, diluviation and alluviation by the playful rivers, excessive flooding during the monsoon, bone-dry desiccation during the dry season, all have repercussions on the agricultural economy of the area and contribute to human miseries. Soils with the present level of low fertility and poor productivity do not seem capable of supporting the population pressure per unit area.

Knowledge of the soil problems of East Pakistan and their scientific solution are still so limited that these fields may be regarded as untrodden. The gap in knowledge is too big to be filled by the meagre contributions of a few soil scientists. The university teachers here use textbooks on soil science written by authors of Western countries. Students coming from the university with masters' degrees know very little about the soils of their own country.

Our pressing need at this moment is to prepare an inventory of soil resources, to be acquainted with the problems of irrigation agriculture, the physico-chemical problems of submerged soils, the causes of poor fertility and the means of improving the productivity of these soils. Research is needed in the fields of mechanized agriculture, fertilizer-variety interaction for different crops, irrigation and drainage techniques, flood control, erosion hazards, soil conservation and crop rotation, etc.

We need not only to create soil scientists, but also to create knowledge of the soils of this country. In this connexion I should like to bring to the attention of all the extreme necessity of establishing an Institute of Soil Resources, Research and Development for this country, so that we can create the knowledge of local soils for the benefit of the students and teachers of soil science and the various users of soils.

Résumé

Sols du Pakistan-Oriental (M. Amirul Islam)

L'auteur donne des renseignements sur les sols du Pakistan-Oriental, exemples de sols tropicaux humides. Il parle des problèmes posés par les sols alluviaux des plaines d'inondations de la région du delta. Les sols du Pakistan-Oriental ont été classés en trois groupes physiographiques et en dix types de sol.

La question de la fertilité de ces sols est étudiée, ainsi que d'autres problèmes pédologiques, tels que les effets de la submersion des sols pendant la mousson, la salinité et la formation de sols « kosh » (*cat-clays*). Étant donné que les sols locaux sont mal connus, l'auteur évoque la nécessité de créer un institut de recherches pédologiques.

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Article by Sioli (see page 89).

PLATE I.
High forest on *terra firme* soil on the right side of Rio Pará, behind Belém.

PLATE II.
Capoeira (secondary growth) in the Zona Bragantina, on the right side of Rio Pará, behind Belém.

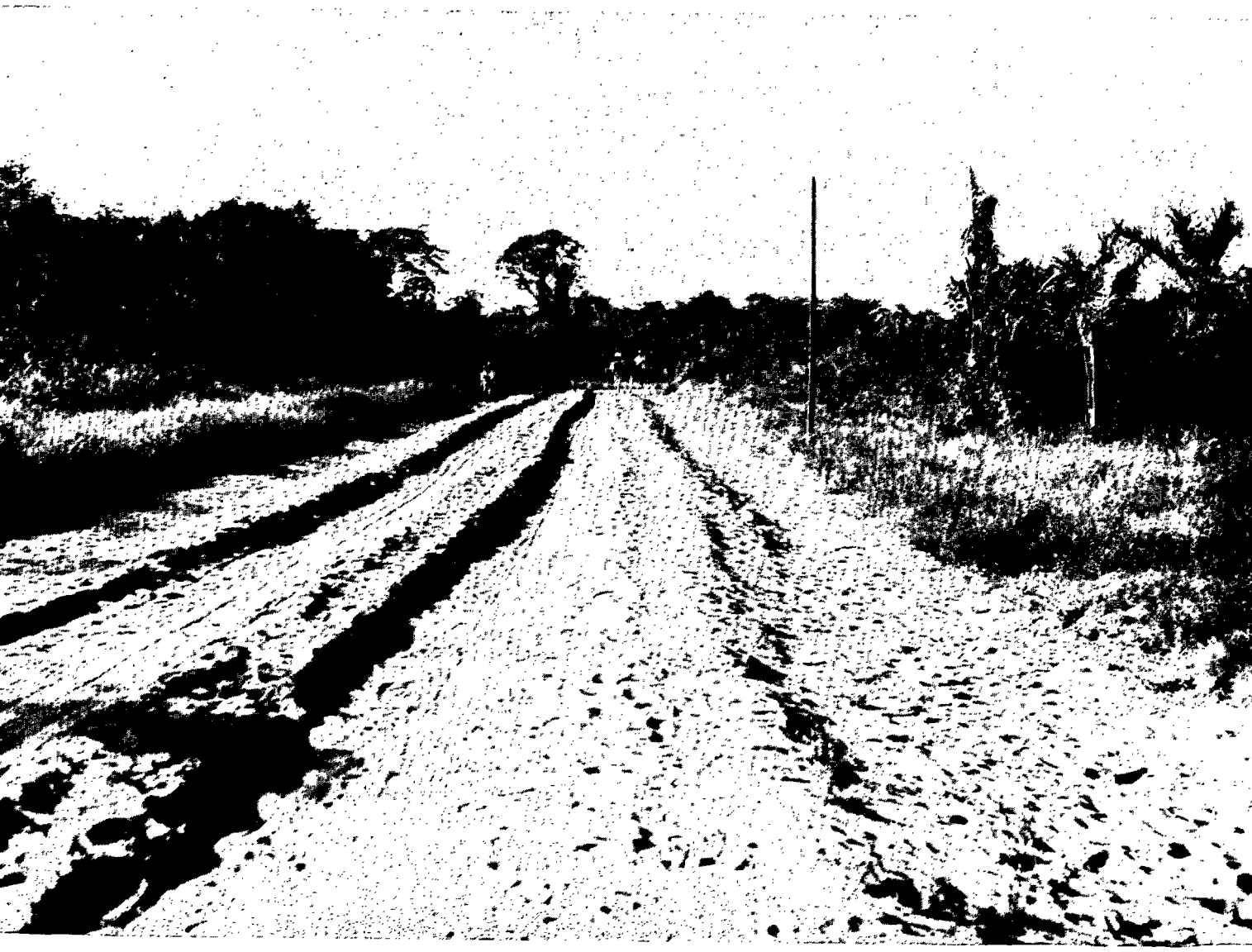


PLATE III.
Campo on bleached sand, with *Mauritia* sp., between Belém and Vigia.

PLATE IV *(overleaf).*
Hard-pan, a thick and hard B-horizon, appears by the action of erosion under the bleached sand of Fig. 2.

Soils in the estuary of the Amazon

Harald Sioli

In the paper on "General Features of the Delta of the Amazon" (see Part VI) it has been pointed out that in that region (Fig. 1) we must distinguish between two main types of terrain: the *terra firme* and the alluvial lands, called *várzea*. While the *terra firme* is above the level of the highest floods, the *várzea* is periodically inundated.

The *terra firme* consists here of old Quaternary sediments of the enormous Amazonian freshwater lake which in the Pliocene-Pleistocene age covered the entire Amazonian lowlands. These sediments, known as *Formação Pará* (probably identical with the *Série das Barreiras* of the Amazonian interior, etc.) are clays, loams and sands, derived mainly from the weathering products of the arquean massifs of granites and gneisses of central Brazil and the Guianas which were transported and deposited into that immense lake.

Already by its origin from granites and gneisses, then by the history of its transportation, contact with fresh water before and after sedimentation for hundreds of thousands, perhaps even some millions of years, this material is to be expected to be poor with regard to mineral reserves which may be liberated by the soil-forming processes.

The alluvial lands are recent deposits of material which have been and continue to be brought down by the Amazon in its turbid, so-called "white water" and by its white-water affluents.

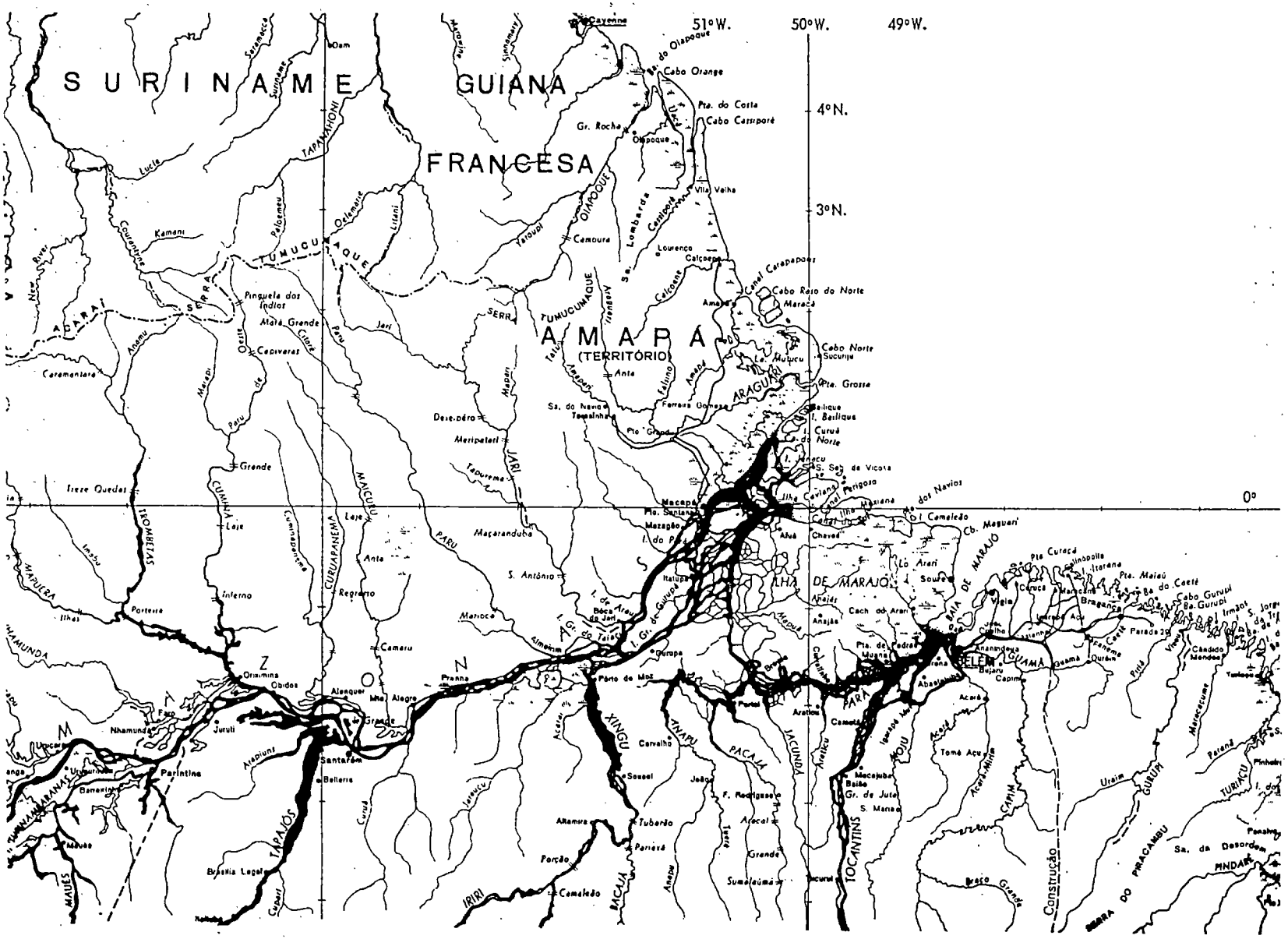
This material has its real origin in mountainous regions where there is strong erosion attacking a strongly undulated, immature relief of the earth surface. If we follow the white-water rivers up to their sources, we find all of them in mountains, be it the ranges along the border to Venezuela and British Guiana, where the turbid water of the Rio Branco originates (the sediments of which, however, do not reach the Amazon, but are deposited in the Rio Negro), or be it the Andes and the forelands where we find the headwaters of the Rio Madeira and of all the large rivers of the western part of Amazonia including the Amazon itself (its name changes to Solimões from the mouth of the Rio Negro up to the Peruvian border, and to Marañon in Peru).

The material of the alluvions is the product of weathering processes acting on manifold bedrocks—not only granites and gneisses—under different climates, generally cooler ones of high mountains. We may therefore expect from the beginning that the alluvial lands will be richer in mineral reserves than are the aforementioned old Quaternary sediment layers of the *terra firme*.

Since the majority of the islands within the Amazon-estuary and also the lower north shore of the outer estuary consist of recent alluvial land, we must go either to the eastern half of the island of Marajó, to the north shore of the upper part of the northern estuary branch, or to the south banks of the Rio Pará in order to find the most extensive stretches of Pleistocene *terra firme* and its respective soils. Of the areas which do not consist of recent fluvial alluvions, the eastern half of Marajó is flooded during several months of the year. On the islands of the Estreitos de Breves there are also patches of such *terra firme* soils, as we may describe them, and they occur in different heights in relation to the water level.

The best examples in the Amazon estuary of such old Quaternary terrains of a higher level (with a ground-water table deep enough so as not to impede the percolation of the upper layers) are situated on the relatively densely-settled right side of the Rio Pará behind Belém, between the Atlantic coast and the Rio Guamá. They have been and are utilized for agricultural purposes. We shall consider the main soil type of that region first.

The surface of all the area was once covered by a high and luxurious forest (Plate 1) which led the settlers to believe that the soils were very fertile. At the end of the last century, colonization by immigrants from north-eastern Brazil was started with the aim of supplying the growing city of Belém with all necessary foodstuff, but the result of that colonization system


SURINAME
GUIANA
FRANCESA
AMAPÁ
(TERRITÓRIO)
ILHA DE MARAJÓ
BELÉM
51°W.
50°W.
49°W.
4°N.
3°N.
0°
Cayenne
Cabo Orange
Pta. do Costa
Cabo Cassiporé
Gr. Rocha
Oiapoque
Vila Velha
Camoura
Lourenço
Calçoene
Cabo Raso do Norte
Maracá
Cabo Norte
Sucuriju
Pta. Grosse
Ferreira Gomes
Macapá
Mazagão
Chaves
Cachoeira
Souza
Anajás
Gurupa
Porto de Moz
Prainha
Almeirim
Santarém
Alenquer
Monte Alegre
Oriximiná
Obidos
Parintins
Manaus
Tefé
Coari
Tabatinga
Benjamin Constant
Boa Vista
Bonfim
Caracaraí
Mucajaí
Tucumaque
Serra do Acaraí
Serra do Ipiranga
Serra do Cachimbo
Serra do Tocantins
Serra do Piracambu
Serra do Desordem
Serra do Mindaú
Serra do Tumucumaque
Serra do Tapajós
Serra do Xingu
Serra do Iriri
Serra do Macaúbas
Serra do Jari
Serra do Paru
Serra do Maicuru
Serra do Curuá
Serra do Trombetas
Serra do Mapuera
Serra do Uraricoera
Serra do Parima
Serra do Tapirapecó
Serra do Cuchinha
Serra do Cupixi
Serra do Tocantins
Serra do Araguaia
Serra do Xingu
Serra do Tapajós

was a failure. In the following decades, almost all the region of about 30,000 sq. km. had been deforested, but no permanent cultures had been installed. After cutting and burning the high jungle, the soil of the *roça*, the clearing, was utilized for the planting of manioca, corn, rice, tobacco, etc., during two or, at most, three years. Then, the harvests became so small, or were such complete failures, that the terrain had to be abandoned. Successively new areas of forest were treated in the same way. In the years following the abandonment of the *roça*, a low secondary forest, the so-called *capoeira*, grew on the spot and could be cut and burnt again after eight to ten years to permit a new plantation which, however, gave an acceptable harvest for only one more year. Afterwards the soil was in many cases completely exhausted and the place was definitely abandoned. Until about 1950 almost 90 per cent of the cited country on the eastern side of the Rio Pará, the so-called Zona Bragantina, had been devastated by that method and abandoned, only about 5 per cent being under cultivation, a result which demonstrated *ad oculos* that the soil was not as fertile as had been presumed. On the contrary it proved the soils to be without nutrient reserves for plant growth: the nutritive substances, necessary for the existence and life of the original vigorous forest, had been accumulated by the vegetation during hundreds or thousands of years and were only circulating within the living matter without any considerable part of them being stored in the soil. By cutting and burning the trees these substances had been immediately liberated in the ashes, a part of which was then used by the planted crops and taken away with the harvest, the rest being washed away by the rains into the creeks and the ground water. In every case, these precious substances were lost to the soils and for future plant growth, and only extremely slowly could they and can they be substituted by new nutrients deriving from continuing weathering processes on the soil and subsoil material, and by those contained in the rainwater in small concentrations. Also, erosion took place on the denuded soils, washing away the finer particles and increasing the sandy character of the surface layers. This degradation obliged the people to rest the soils more and more but even so the vegetation recovered very slowly. In the Zona Bragantina there are *capoeiras* of ten to fifteen years of age composed only of small bushes which in certain parts of the upper Amazon would correspond to secondary growth of only one year or even less (Plate 2).

Such experiments have been made not only on the *terra firme* soil near the Amazon estuary but almost everywhere on the *terra firme* throughout the interior of Lower Amazonia. With regard to nutrient reserves for plant growth, the *terra firme* soils are identical, with some restricted local exceptions, over the whole of the country cited. (In Upper Amazonia, near the Andes, where the *terra firme* also received, and receives, the weathering products of those mountains, richer soils are found but these will not be considered here.) It was a long time before the first studies of Amazonian soils were made by Marbut and Manifold in the middle of the twenties of this century. These studies, in spite of being simple research (Fig. 2) demonstrated for the first time the chemical poorness of these soils. They compared them with the poor soils of the coastal plains of the south and south-east of the United States (Marbut and Manifold, 1926). The Amazonian soils, however, were a little more clayey and heavier; the American soils had a greater quantity of silica (SiO_2), the Amazonian soils were richer in iron and aluminium (Fe_2O_3 and Al_2O_3). These contents increased towards the subsoil from an average of 4.26 to 5.95 for iron and from 14.61 to 19.18 for aluminium, a phenomenon which is perfectly normal in lateritic soils. With regard to mineral salts the American as well as the Amazonian soils were extremely poor. In the former, however, the average content of calcium, potassium and magnesium was slightly better, while the latter had a little higher content of nitrogen. It was only during and after the Second World War that the Instituto Agronômico do Norte in Belém (Pará), under the directorship of Dr. Felisberto C. de Camargo, started with the first modern soil analyses in the Brazilian Amazon region. At the same time chemical studies on the Amazonian waters, made by the author, revealed such an extreme poorness of dissolved salts in the creeks and rivers of the largest part of the *terra firme* and also of those in the Zona Bragantina, that these waters could best be compared with a "not very pure, distilled water". This limnochemical fact also demonstrated the poor mineral reserves in the soils and the subsoils which normally are liberated by weathering and soil-forming processes and, under a cover of climax vegetation, should then show up with the ground water, in the springs and creeks.

Hence it became definitely clear that the high exuberant forest does not exist on these soils because of their —imagined—fertility, but only and solely due to the fact that it represents vegetation in a climax state which has enough self-accumulated nutrients to stay in equilibrium with its environment, and is therefore practically independent of nutrient supply from the soil.

The predominant type of that higher *terra firme* soil of the Amazon estuary is of a yellowish-brownish colour, has a high content of quartz sand, good drainage, and is acid. However, in many places there are layers of iron concretions in certain depth; by superficial or lateral erosion that so-called "canga" stone, formerly designated also as "laterite", may now appear on the surface of the ground as thick cuirasses, or on the cliffs of river shores in the form of big blocks. Such soils are generally not uncommon in the tropics. They are usually classified in the great group of "latosols". Some examples from Belém and from Breves showed $\pm$ 85 per cent quartz sand particles, pH values between 4.14 and 4.9 and very small amounts

of Ca^{++} (0.20 meq./100 g.), Mg^{++} (0.10 meq./100 g.) and K^{+} (0.08 meq./100 g. on the surface, 0.02 meq./100 g. at 10 cm. depth), while P_2O_5 dropped to 0 at 10 cm. depth. The small amounts of the latter, if existent at all, are furthermore generally bound to iron and not available for plant growth. Examples of this soil are described by Camargo (1949*a*) and by Vieira and Santos (1962).

The same material of identical, i.e., old Quaternary, origin can be, however, subjected to the influence of a higher ground-water level, and then a gley soil develops. Reduction conditions prevail, and are easily verified by the grey colour of that soil, mainly in the B horizon. Since the water, which may periodically even cover such terrains, is no white-river water but accumulated rainwater with delayed run-off, no sedimentation takes place, and we may therefore explain these sections as being "drowned *terra firme*".

A soil sample of this type from near Breves has been described by Vieira and Santos (1962). The chemical characteristics consisted in high acidity (pH 3.5) with ferrous ion in exchangeable form, and a low content of assimilable phosphate. Sand was present in only 54 per cent, against 34 per cent and 12 per cent clay in the surface layer, the drainage was moderate to imperfect. The content of Ca^{++}, Mg^{++}, and K^{+} was in the same order as in the latosol, and also P_2O_5 descended to 0 at 10 cm. depth.

Apart from these two soils of non-alluvial origin, there is still another soil in the Amazon estuary which has not been deposited by recent fluvial activity, but which also does not have its origin in the sediments of the Pliocene-Pleistocene Amazonian freshwater lake. This soil occurs in the form of local deposits of grey, sometimes even nearly white, almost pure quartz sand. The material has probably been the sand deposited on river- or ocean-beaches or of sand-dunes which later have been overgrown and incorporated into the firm land of different height.

Such grey or bleached white sands are found scattered in many parts of the interior of Amazonia, and where they occur they carry a special type of vegetation whose variations apparently accord to conditions relating to the water-household of the soil and subsoil. Another curious fact is that the ground water in these zones is always brown to red-brown "black" water; it also appears in springs as a source for the typical "black-water creeks". The predominance of the grey or bleached white sands, e.g., in the upper Rio Negro region (cf. Richards, 1952), gives the landscape its peculiar character: wide extensions of the area are occupied by the so-called *caatingas*, a lower, open and scanty forest-type of specific floristic composition, where the creeks and rivers carry black water; the big Rio Negro itself is the classical example of that type of river. Around Manáus, patches of equally bleached sands bear the poor *campina* vegetation which is no longer a forest but a tree and bush savannah. At the estuary

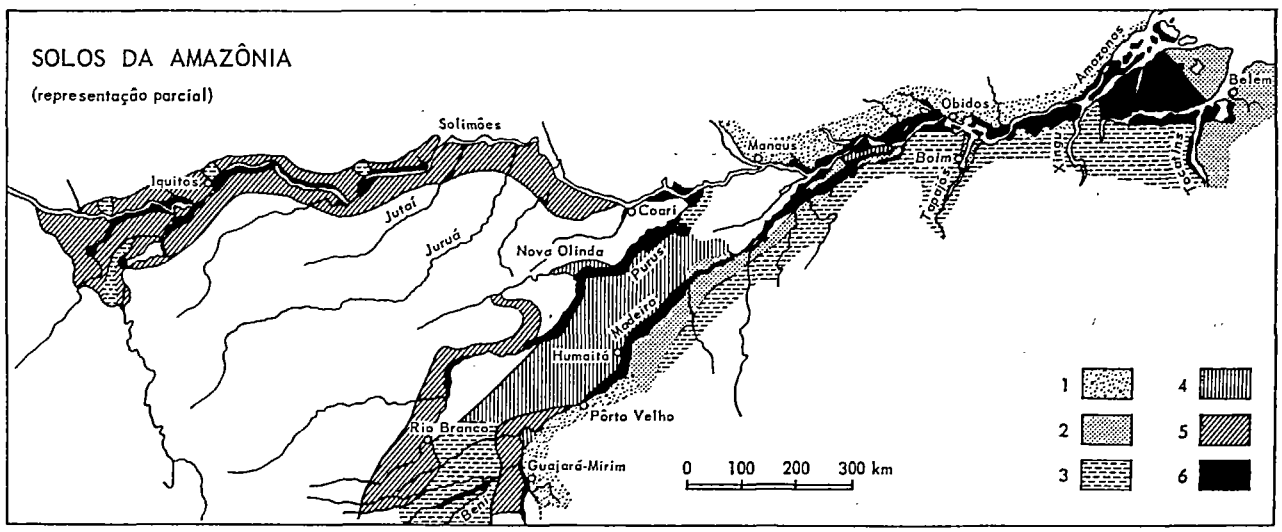


FIG. 2. First soil map of the Amazon region (after Marbut and Manifold, 1926). (Reproduced from IBGE, Geografia do Brasil, Grande Região Norte, Bibl. Geogr. Bras., vol. 1, 1959.)

Explanation of key:

1. Sandy loams with yellow, brittle subsoils generally consisting of sandy clays.
2. Fine sandy loams with subsoils of predominantly clays or sandy brittle, yellow or yellow-reddish clay.
3. Clayey loams and clays with subsoils of brittle red op reddish clay.
4. Clays and clayey loams with subsoils of heavy and imperfectly oxydated clay, at a depth of 60 cm. (2ft or more).
5. Very fine, sandy loams with subsoils of brittle red or yellow-reddish clay.
6. Alluvial soils.

of the Amazon there are identical sands, for instance behind the north shore near Macapá, near Breves, on the road between Belém and Vigia, etc.

Chemical analyses of the black waters of the upper Rio Negro region made almost twelve years ago by the author, gave the first hint that in the *caatinga*-covered, bleached sands of the headwater zone, podzolization processes occurred. While in the clear-water creeks, coming from brown loams with high forest cover, aluminium had never been detected, the black water always had a small but certain content of that element; also the iron content was generally higher than in the clear waters, while the silica content was less. The black waters were also even more acid, with pH values between 4.2 and 3.8. These findings showed that aluminium and iron emigrated from the soil, while silica remained more stable, a situation which corresponds to podzolization.

Later, soil samples were taken from the "bleached sands" of the upper Rio Negro and of the area of Manáus which proved the existence of true podzols—formerly doubted in the tropics—associated sometimes with a heavy, compact, black to brown B horizon, a hard-pan, which in other sands was lacking. Last year Dr. Hans Klinge of the Hydrobiologische Anstalt der MPG, spent three months on the Amazon studying the podzols, among which are two perfect and instructive occurrences in the estuary, between Belém and Vigia, each with a thick and hard B horizon. One was a low and open *campo* of Cyperaceae, Eriocaulaceae, and some palm trees of the genus *Mauritia*, which was flooded in the rainy season by ascending brown ground water (Plates 3 and 4). The other example was situated higher with a deeper ground-water level and covered with poor bushes. The results of those pedological studies are to be published.

In the meantime Vieira and Santos (1962) described such grey soils of pure sands from the neighbourhood of Breves, among the alluvial lands west of Marajó, and classified them as regosol-podzol association, the latter being a developed state of the first one. In the region of their study—from Breves 12 km. landward through forest—the stretches of these soils are well exposed and occupy nearly 50 per cent of the area. The forest on these soils is not so exuberant as is common in the Estreitos de Breves, the trees being only of medium height. In the regosol, there occurred only the A and C horizons, in the podzol a good sequence of A_1, A_2, B_h, B_{2ir} and C was developed. Above the mineral material, there was a notable layer of organic matter which formed the A_{00} and A_0 sub-horizons generally 20 cm.

In the hydromorphic podzol profile the pH was 4.1 in the A_{11}, between 0 and 12 cm. (below the A_{00}, A_0), rising to 5.8 in A_2 and falling again to 4.0 in B_h. K^+ is in the same order as in the latosol or in the gley near Breves, analysed by the same authors, but Ca^{++} and Mg^{++} are a little higher, mainly in the A horizons; P_2O_5 is also higher throughout the whole profile. Al_2O_3 and Fe_2O_3 are naturally much lower here than in the latosol, but with an enrichment of Fe_2O_3 in the B horizon, mainly in the B_{2ir}.

For more details concerning this soil type, the publication of Vieira and Santos (1962) should be consulted. This type, although not so common in the Amazonian estuary, is specially interesting, because the localities where it occurs must once have been sandy beaches, either of the ocean or of wide open freshwater surfaces, or they were sand-dunes near the coastline. So the "bleached sand" area between Belém and Vigia may be taken as an old shoreline; the sands near Breves were perhaps beaches on the western side of the *terra firme* nucleus of Marajó, before the space between this island and the continent had been filled with the labyrinth of islands of the Estreitos de Breves.

No studies have ever been made on the soils of the mangrove girdle along parts of the Atlantic coast of the Amazon estuary. Hence nothing can be said about them.

The most interesting soils of the region are the recent alluvial lands deposited by the turbid, rich-in-sediment river water. The area which is covered by these alluvions has never been measured exactly because of the lack of maps indicating the limit between *terra firme* and the flood-plain. Therefore it is not really known. According to the estimate made by Marbut and Manifold (1926), at least half of the land surface of the Amazon estuary may be alluvial. But since Vieira and Santos (1962) described stretches of *terra firme* in the hinterland of Breves on the most western part of the island of Marajó, we must accept the possibility that not all of what Marbut and Manifold described as alluvial soils is in fact so. Camargo (1949*b*) speaks of "not less than 1.5 million hectares" (15,000 sq. km.) formed by the Amazon river in its estuary. In this estimate the alluvial lands along the coast of Brazilian Guiana, of the Território Federal do Amapá, are evidently not included as they alone would comprise an additional 12,000 sq. km. Lima (1956) calculates that the total areas of land subject to floods in the estuary of the Amazon amount to nearly 2.5 million hectares (25,000 sq. km.) but he does not say whether the coastal zone north of the mouth of the Amazon should be included or not. Perhaps it is not too far from reality when we assume 25,000 to 30,000 sq. km. to be the extension of recent alluvial land in the whole Amazon estuary.

Since the affluents of the lower Amazon are all clear- or black-water rivers which add extremely little or nothing to the sediment load of the Amazon, the initial material of the alluvial lands must have been brought a long way down from the western regions of the Amazonian potamic system, i.e., with the turbid white-water rivers. That material, however, does not move over the whole distance from the Andes to the mouth in a single bound, but is the product of multiple sedimentation and erosion. And it seems that it is not

the Andes uplands themselves which actually furnish the greatest quantity of the suspended material in the Amazon water, because the streams and rivers of the uplands have clear water which turns turbid only after reaching the lower lands east of the Andes. There the rivers may even be muddy torrents which contribute vigorously to the drainage system of the country. So it seems that, after the uplift of the Andes, first the immense lowlands to the east are filled with the weathering products of these young mountains, and that it is this accumulated material of that enormous alluvial plain in the forelands of the Andean range which is successively transported down the river until it finally reaches its estuary and the ocean. And even there, in the estuary, a certain translocation of the alluvions and a continuation of deposition of recently sedimented material may occur for the following reasons.

First because the turbid water in the estuary seems to have a greater quantity of suspended solids per litre than the lower Amazon itself. Near Santarem determinations by the author showed a content of always less than 200 p.p.m. of suspended solids after incineration; Katzer (1903) also communicates very similar amounts of suspended particles for the Amazon off Obidos at different depths, namely 135 and 63 p.p.m. after incineration. In the lower Rio Guamá, however, upstream of the Instituto Agronômico do Norte at Belém with the tides moving in (i.e., in the in-flowing water of the Rio Pará), the suspended solids after incineration were 656 p.p.m.; or, after Katzer, the water of the Estreitos de Breves had 683 p.p.m. suspended solids, more than half of them, however, being organic substances. These differences are so large that they are not the result of a mere coincidence. It seems that the constant fluctuation of water back and forth in the channels of the inner estuary increases the amount of the suspended solids in the water till it reaches a temporary equilibrium between the process controlling sedimentation and transportation.

The reason for the assumption of continuing deposition in many parts of the estuary is also seen in other facts. The vertical growth of the zones periodically flooded by suspension-rich water proceeds in an asymptotic approximation to the level of the highest floods; this point, however, is still far from being reached along the largest stretches of terrain. Furthermore, direct evidence of deposition in the alluvial shore land of the Rio Guamá can be given.

Because of the formation of natural levees, the so-called *várzea* is highest near the river shore while towards the flood-plain the terrain slopes off. If, due to incoming tides, the river overflows, it will not do this equally over all stretches of the natural levee, because there are openings in the levee, most of them being formed by small affluents, or by the back-flowing flood-water. The flood enters and leaves through these openings of the natural draining system of the *várzea* and onyl behind the natural levee does it spread out over the whole area. During this process the suspension load of the water of the Rio Guamá was compared, first one hour after it started to enter the *várzea* through such a natural opening in the natural levee with the incoming tide, and then one hour after the same water started to flow back with the outgoing tide. The respective amounts of suspended solids after incineration were for the entering water (as explained above), 656 p.p.m., then, for the out-flowing water, 575 p.p.m. It can be concluded that 81 p.p.m. of suspended solids were retained in the *várzea*.

At that time the average thickness of the high-water sheet over the *várzea* terrain was ± 25 cm., and from that we can calculate that the flood left ± 200 kg. of mineral sediments per hectare on the flooded terrain. That is a very thin layer of only 0.01 to 0.02 mm. thickness, but in three months of the rainy season of that year there were at least twenty-eight floodings of the same height; thus in the course of time the piling up of the *várzea* land will be notable (cf. Lima, 1956).

The alluvial lands of the Amazon estuary are genetically identical with the *várzea* of the lower Amazon. But there is one great difference which is important for the soil development as well as for the vegetation cover: the *várzeas* of the lower Amazon are flooded only once a year and then, during weeks or months, the flood-lands of the estuary are subject to tidal floods twice a day. These frequent floods regulate the water-house-hold of the alluvial soil in the estuary and impede a periodic drying as happens in the *várzeas* of the lower Amazon, even with the formation of mud-cracks. The deposition of new thin layers of fresh alluvions is constant throughout the whole year and not restricted to certain months only.

These facts have their effects on the living conditions of the vegetation. Together with the mineralogical composition of the initial material, they are the reason that the alluvial lands of the estuary have been considered as the most fertile areas of Brazilian Amazonia (Camargo, 1949; Lima, 1956), even before soil analyses had been carried out. A modern utilization scheme of these lands, even with water control, was recommended and started by the Instituto Agronômico do Norte some fifteen years ago.

The first studies of the alluvial soil from the Rio Guamá at that institute were made by Vageler and published by Camargo (1949*b*). According to him the material of these soils is the mud formed by the decomposition and erosion of old sedimentary and acid volcanic rock. It is heavily leached and contains appreciable amounts of humic acids. The soil contains from 10 to 15 meq. exchangeable bases, their saturation is between 35 and 60 per cent, the pH 4.5 to 5.5. The saturation of the complexes by Na is very weak, only 1 to 3 per cent. P_2O_5 is present in appreciable quantities, bound essentially to iron but with a certain solubility

due to the content of humic substances. The mineralogical reserve is small. "The *várzeas* are in continuous hydromorphic evolution. Inundated or at least saturated every day by the tides, retaining the flow of the rivers, these soils are typical gleys from top to bottom, clay silts to silty clays containing 50 to 75 per cent of fine sand and silt. The A horizon, containing up to 3 per cent of humus, varies within wide limits between 2 and 35 cm. and more. The permeability of the profiles is low (1-2 mm./hr./ha.) notwithstanding the relatively high percentage of non-capillary porosity (7 to 15 per cent). But the availability of the soil water is excellent: ± 40 per cent, a very high field capacity being combined with a very low 'permanent wilting point'.

"There is no danger of being salted for these soils. Every excess of salts always goes back to the rivers with the backflow of the low tides." (Camargo, 1949*b*, p. 602.)

Lima (1956) examined not the evolved soils of the *várzeas* of the Rio Guamá but the suspended matter of the river water which regularly contributes to the alluvial lands by the flooding. The coarsest particles of that matter were fine sand, with an average of 13.5 per cent in the air-dry suspensions; the silt fraction occupied 58.5 per cent, the clay fraction 23.5 per cent, the organic matter 2.5 per cent. The chemical analyses gave as average results in meq./100 g.: Ca^{++}, 7.40; Mg^{++}, 8.41; K^{+}, 1.72; N, 13.23; P_2O_5, 0.22. The pH was 4.5.

Though the amounts of mineral nutrients in the initial material for the alluvial soils are low, they contribute by their continuous delivery to the maintenance of fertility over much longer periods than happens with the *terra firme* soils. Perhaps some artificial fertilization or even only some system of shifting cultivation may make those *várzeas* suitable for a permanent agriculture.

In every case removal of the original forest cover and utilization of those lands, which are in constant transformation by erosion and sedimentation activities of the rivers, will not lead to rapid degradation and to unrepairable, or only very slowly repairable, damage of the land as in the case of the Amazonian *terra firme*. The waste of natural resources must also be avoided, mainly with regard to the soils, and the different soils of the Amazon estuary provide a good example of how that can be done.

Résumé

Les sols de l'estuaire de l'Amazone (Harald Sioli)

L'estuaire de l'Amazone est constitué par deux grands types de terrain : la « terre ferme » et les terres alluviales appelées *várzea*. La terre ferme à l'abri des inondations (à l'exception de certaines régions basses) se compose de sédiments sablonneux-limoneux-argileux du début de l'ère quaternaire provenant du lac d'eau douce amazonien qui, à l'époque du pliocène-pléistocène, couvrait le pays des Andes à l'Atlantique. Les couches provenant surtout de roches de granit et de gneiss d'origine archéenne sont pauvres en réserves minérales.

La *várzea* est de formation récente, elle est due à l'action du fleuve et composée de boues formées par la décomposition et l'érosion des vieilles roches volcaniques acides et sédimentaires des Andes. Alors que dans le bassin inférieur de l'Amazone les *várzeas* sont inondées tous les ans par les crues saisonnières du fleuve, dans l'estuaire, elles sont inondées deux fois par jour par les marées océaniques.

Les sols de la « terre ferme », qui n'est jamais atteinte par l'eau, sont des sols latéritiques, qui présentent souvent des couches dures et épaisses de *canga* que l'on appelait aussi autrefois latérite. A l'état naturel, ces sols latéritiques sont généralement recouverts de hautes forêts. Néanmoins, les réserves minérales y sont très rares. La richesse de la forêt est due aux substances nutritives accumulées pendant des centaines et des milliers d'années qui circulent constamment, transportées par la matière vivante. C'est pourquoi il arrive que la fertilité de ces sols soit épuisée en deux ou trois ans après que la jungle primitive a été abattue et brûlée pour l'établissement de plantations. Sur des étendues exceptionnellement basses de terre ferme, un sol à gley se forme à partir des mêmes substances qui, sur les terres où le niveau de la nappe souterraine est plus bas, forment les sols latéritiques mentionnés plus haut.

Certaines parties de l'estuaire de l'Amazone sont recouvertes par endroits de plaques de regosols et de podzols sur des sables lessivés, qui sont les vestiges de lignes côtières ou de dunes de sable.

Les sols les plus intéressants, parce que les plus caractéristiques de l'estuaire de l'Amazone, sont ceux qui se sont formés sur les alluvions fluviales récentes, qui occupent probablement 25 000 à 30 000 km² et sont empilées de manière à former à peu près une asymptote par rapport au niveau supérieur de crue, sous l'effet de la sédimentation qui se poursuit pendant chaque période d'inondations. En raison du niveau constamment élevé de l'eau ou tout au moins de la saturation constante en eau, ces sols sont des sols à gley. Ce sont

les plus fertiles et les plus riches en minéraux de tout l'estuaire de l'Amazone; ils sont donc particulièrement propres à une utilisation agricole, sous réserve d'un système de régularisation du régime des eaux qui prévienne les risques de gaspillage et de destruction de cette précieuse ressource naturelle qu'est le sol.

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Nutrient status of different soil tracts of East Pakistan

A. Q. M. B. Karim

INTRODUCTION

East Pakistan is in the humid tropic region. The annual rainfall in different parts of East Pakistan varies from 70 to 120 inches. The temperature is also high, ranging from 75° to 108°F. The high rainfall and the many rivers and channels flowing through this land make it an evergreen land. Forests, agricultural crops, shrubs, grasses, etc., grow there in abundance throughout the year. There would appear to be no nutritional problem for the plants growing in this region, but in fact there is. The crop yield per acre of land is very low as compared with that of the inland areas.

On account of the many rivers and their tributaries flowing through this land, the soils of a big area in and around them are enriched every year with fresh deposits of silt carried down by the flood-water. This part of the land remains waterlogged for about six months and is dry for the rest of the year. The soil of this region supports mainly jute, rice and sugar-cane together with a wide variety of other crops. The topography of this low land is flat.

The high-land area generally does not receive flood-water and is therefore deprived of the fresh deposits of silt and clay. The soil of the high-land region is heavily leached every year during the monsoon period. In between the high lands there are many depressions, which receive rain-water from the surrounding upland. The soil in the upland area supports mainly forest trees, shrubs, grasses, vegetables, etc., and the soil in the depression is mainly used to grow rice.

Because of the diversity of actions of the natural forces stated above it may be expected that there will be variations in soil properties, including the nutritional status of soil, ultimately affecting the plant growth in different parts of East Pakistan.

Due to the lack of knowledge of scientific methods of soil management as well as of soil research amongst the farmers of East Pakistan, very little was known in the past as to the soil requirement and mineral deficiency of crops growing in this country. But, in the recent past, by consolidating the research activities of the different scientific institutions of East Pakistan on soil and fertilizer requirements it has been found that most of the soils here mainly need nitrogen and phosphorus and in some cases potassium for better growth and yield of field crops. There remains no doubt now that with proper application of fertilizers to our soil, the crop production can be increased tremendously.

EXPERIMENTAL

For correct assessment of the fertilizer needs of the soils of East Pakistan we have been trying for the last few years to find out the nutritional status and the mechanical composition of these soils in the different soil laboratories of East Pakistan. The soils are generally classified into four tracts: Brahmaputra, Gangetic and Tista new alluvium; Madhupur and Barind old alluvium; coastal saline soils of Khulna, Barisal and Chittagong; soils of Chittagong hill tract.

The nutritional status in terms of organic matter, total nitrogen, available phosphorus, potassium and calcium and the mechanical composition mainly of the surface soils from these tracts were determined. More work is to be done to obtain full information regarding the needs in fertilizers of these soils. The mechanical composition of some soils from these tracts is presented in Table 1.

DISCUSSION

Mechanical composition

The tract consisting of new alluvium represents riverine lands of the flood-plains of the Brahmaputra, Ganges, and Tista rivers and covers an area of 33,000 sq. miles. The land spreads over several districts of East Pakistan: Comilla, Noakhali, parts of Sylhet, Mymensingh,

Dacca and Chittagong are traversed by the Brahmaputra; Jessore, Kushtia, parts of Rajshahi, Pabna, Faridpur, Khulna, Barisal and Dacca are covered by the Ganges; parts of Rangpur, Dinajpur, Bogra and Pabna are traversed by the Tista river. Texturally the soil varies mostly from sandy loam to silty loam with easy drainage. The soil is generally fertile.

Madhupur and Barind tracts cover an approximate area of 9,000 sq. miles consisting of high lands with many depressions between them. Some soils are of a red colour with high contents of iron (7 to 8 per cent) and some are pale reddish-brown containing less iron. All these soils are old alluvium. Texturally they range from clay loam to silty clay. The soils in the upland area are relatively poor in fertility.

The coastal saline soil of Barisal, Khulna, Noakhali and Chittagong district covers an area of 6,000 sq. miles. The topography of this region is flat. The land borders the Bay of Bengal and receives sea-water occasionally. Soils range mostly between silty clay loam and clay loam in texture and are suitable for rice cultivation.

The soil of the Chittagong hill tract and Garo hills in Mymensingh spreads over an area of 6,000 sq. miles. The soil in the hill tract is poor in fertility and mostly covered by forest but *jhum* cultivation is practised in this area. The soil in the valley (hill base) is moderately fertile; texturally it is sandy loam to loamy sand with free drainage.

Nutrient contents of soils

The values for the organic matter, total nitrogen, available phosphorus, potassium, calcium and the pH of the different soil tracts of East Pakistan are presented in Table 2.

Organic matter. In all the soil tracts under study, the saline soils contain the greatest amount of organic matter varying from 2.5 to 2.79 per cent. The new alluvium and the soils of the Chittagong hill tract contain a relatively lower amount of organic matter varying from

TABLE 1. Mechanical composition of soils (as percentage of air-dry soil)

Location	Sand	Silt	Clay	Textural class
		New alluvium		
Dacca:				
Narshindi	79.1	6.2	11.4	Loamy sand
Hazipur	78.46	6.83	11.01	Loamy sand
Sree Nagar	83.25	3.3	10.25	Loamy sand
Baduichar	79.01	6.2	11.4	Loamy sand
Baty Badarpur	69.03	16.5	12.48	Sandy loam
Mymensingh	35.2	49.3	14.1	Loam
Banbari	54.42	19.8	22.06	Sandy loam
Berberi	54.7	24.21	18.14	Sandy loam
Parijatpur	19.47	59.74	21.24	Silt loam
Darisaya	12.04	57.79	29.02	Silty clay loam
		Old alluvium		
Sreepur	50.65	22.36	25.44	Sandy clay loam
Dardaria	53.05	20.95	25.13	Sandy clay loam
Karnapur	51.49	28.97	18.7	Sandy clay loam
Mirpur	45.2	20.4	33.9	Clay loam
Fayzabad	28.34	29	39.7	Clay loam
	28.6	20.5	41.2	Clay loam
		Saline soils		
Khulna:				
Suter Khali	7.14	53.6	34.4	Silty clay loam
	8.35	54.5	30.8	Silty clay loam
Joymongirgol	8.6	51.5	35.13	Silty clay loam
	9.43	53.62	36.2	Silty clay loam
Khulna suburb	10.47	51.9	35.7	Silty clay loam
	7.7	56.9	34.3	Silty clay loam
		Chittagong hill tract soils		
Rangapani	53.17	22.36	16.76	Sandy loam
	54.75	19.28	21.12	Sandy clay loam
Khadanjee	55.45	23.62	15.2	Sandy loam
Chittagong suburb	55.88	20.1	20.45	Sandy clay loam
	53.65	22	21.4	Sandy clay loam

TABLE 2. Nutrient status range in different soil tracts as percentage of air dry-soil

	New alluvium	Old alluvium	Saline soils	Chittagong hill tract soil
Organic matter	1.3 to 1.5	1.12 to 1.17	2.5 to 2.79	1.39 to 1.53
Total nitrogen	0.05 to 0.1	0.05 to 0.06	0.16 to 0.174	0.078 to 0.083
Available P_2O_5	0.02 to 0.1	0.07 to 0.08	0.1 to 0.12	0.06 to 0.09
Available K_2O	0.9 to 1.2	0.7 to 0.9	0.4 to 0.5	0.6 to 0.8
Available CaO	0.3 to 2.6	0.34 to 0.48	0.95 to 1.1	—
Exchangeable manganese (in p.p.m.)	35.2 to 36.6	98.8 to 101.1	31.2 to 34.97	34.8 to 35.7
pH:				
Brahmaputra	4.5 to 6.5	4.6 to 6.5	6.9 to 7.5	5.2 to 5.6
Gangetic	7 to 8.5	—	—	—
Tista	5.5 to 6.5	—	—	—

1.3 to 1.53 per cent, the least amount being found in the old alluvium of the Madhupur and Barind tracts. In all these soils the low value of organic matter is quite expected on account of the high temperatures of this region; the variation in different tracts is due to the difference in crop pattern and soil management.

Total nitrogen. The total nitrogen content of these soils follows the same trend as shown by their organic matter content. Thus the total nitrogen content is highest in the saline soils, ranging from 0.16 to 0.174 per cent, whereas the new alluvium and the soils of the Chittagong hill tract contain almost identical amounts of total nitrogen which are slightly lower than that in the saline soil. The old alluvium appears to contain the least amount of total nitrogen. Since the old alluvium is an upland soil it is leached heavily during the rainy season, therefore the least value for nitrogen in this soil is not unexpected.

Phosphorus. The saline tract of Khulna is also the soil richest in phosphorus, which varies from 0.1 to 0.12 per cent. Such a result is quite expected due to the soil's high content in organic matter. The old alluvium and the Chittagong hill tract soils contain a relatively lower amount of phosphorus varying from 0.06 to 0.09 per cent. The phosphorus content of the new alluvium is surprisingly variable. Gangetic and Tista alluvia contain a similar amount of phosphorus (0.11 to 0.13 per cent), like that of the saline soil whereas in the Brahmaputra alluvium it is significantly low (0.02 per cent).

Potassium. Although the saline tract is considerably rich in nitrogen, phosphorus and organic matter its potassium content is the least (0.4 to 0.5 per cent) of all the soils under study. The new alluvium soils of the Gangetic, Tista and Brahmaputra regions appear to contain the greatest amount of potassium (0.9 to 1.2 per cent). The potash contents of the old alluvium and the Chittagong hill tract soils are moderate (0.06 to 0.9 per cent).

Calcium. Calcium content of the old alluvium is found to be the least (0.34 to 0.48 per cent) of all soils. Saline soils contain a moderate amount of calcium varying from 0.95 to 1.1 per cent. In the new alluvium calcium content varies considerably. The Gangetic alluvium contains the highest amount of calcium (2.6 per cent) followed by the Brahmaputra alluvium (0.62 per cent (whereas the soil in the Tista region is very poor in its calcium content (0.3 per cent).

Exchangeable manganese. The exchangeable manganese content of the old alluvium with high content of iron is considerably high (98.8 to 101.1 p.p.m.); but in the new alluvium, saline soil of Khulna and the Chittagong hill tract soil, its content is relatively low, varying from 31.2 to 36.6 p.p.m.

pH of soil. The pH of the new alluvium of the Brahmaputra, Ganges and Tista rivers is notably variable, the values varying from 4.5 to 6.5, 7 to 8.5 and 5.5 to 6.5 respectively. The high pH value of the Gangetic alluvium may be attributed to the presence of a relatively greater amount of calcium in the soil. The old alluvium and the Chittagong hill tract soils are distinctly acid and their pH values range from 4.6 to 6.5 and 5.2 to 5.6 respectively. The saline soil of Khulna is neutral but tends to be on the alkaline side. Its pH varies from 6.9 to 7.5.

CONCLUSION

From the above discussion it seems clear that of all the soil tracts of East Pakistan, the saline soil of Khulna appears to be the best in fertility although its potash content is relatively very low. The new alluvium of the Brahmaputra, Ganges and Tista rivers and the Chittagong hill tract soils hold a middle position in respect of their fertility whereas the old alluvium of the Madhupur and Barind tracts is poor in nutrient contents.

Résumé

Les propriétés nutritives du sol dans les différentes régions du Pakistan-Oriental (A. Q. M. B. Karim)

Le Pakistan-Oriental est situé dans la zone tropicale humide. La pluviosité, l'humidité et la température présentent de légères variations entre ses différentes régions. La topographie de ces régions varie aussi dans une certaine mesure. L'existence de nombreux cours d'eau rend encore plus compliquée une étude générale des sols du Pakistan-Oriental.

Les sols des différentes régions sont très divers du point de vue de la composition chimique et mécanique. Si l'on tient compte de tous les éléments qui déterminent leurs propriétés, les sols du Pakistan-Oriental peuvent se classer en trois régions : *a*) alluvions récentes du Brahmapoutre, du Gange et de la Tista; *b*) alluvions anciennes de Madhupur et Barind; *c*) sols salins côtiers de Khulna, Barisal et Chittagong.

La région d'alluvions récentes représente les territoires riverains des aires d'inondation du Brahmapoutre,

du Gange et de la Tista. Les terres qui s'étendent des deux côtés des fleuves sur de larges portions de plusieurs districts du Pakistan-Oriental sont enrichies chaque année par de nouveaux dépôts de limon transportés par l'eau d'inondation. Par leur composition granulométrique, les sols varient pour la plupart de la terre sablo-limoneuse à la terre limoneuse. Le *p*H des dépôts alluviaux du Brahmapoutre, du Gange et de la Tista varie de 4,5 à 6,5, de 7 à 8,5 et de 5,5 à 6,5 respectivement. Les teneurs en azote, en phosphore, en potassium, en matières organiques et en calcium varient de 0,05 à 0,1; de 0,02 à 0,1; de 0,9 à 1,2; de 1,3 à 1,5 et de 0,3 à 2,6 % (pour un sol séché à l'air) respectivement. Le sol produit principalement du jute, du paddy et de la canne à sucre, ainsi qu'une grande variété d'autres plantes cultivées.

Les régions de Madhupur et Barind forment une zone de hautes terres séparées par de nombreuses dépressions. Certains sols sont rouges et ont une forte teneur en fer, et certains sont brun rougeâtre pâle et contiennent moins de fer. Tous les sols sont des alluvions anciennes et, du point de vue granulométrique, ce sont des terres limono-argileuses à argilo-limoneuses. Leur teneur en matières organiques est légèrement inférieure à celles des alluvions récentes. Leur contenu en azote est presque identique, tandis que le calcium et le potassium y sont beaucoup plus rares que dans les alluvions récentes (à l'exception de la vallée de la Tista pour ce qui est du calcium). Leur teneur en phosphore est également faible. Le *p*H est nettement acide (4,6 à 6,5).

Les sols salins côtiers sont pour la plupart argilo-limoneux à limono-argileux. Le *p*H du sol est neutre, à tendance alcaline. Les sols sont relativement riches en azote total, matières organiques et phosphate. Ces sols contiennent également du calcium, en quantité modérée, mais sont relativement pauvres en potassium.

Les sols des hautes terres de Chittagong sont sablo-limoneux à sablo-argileux. Leur *p*H varie dans la plupart des cas de 5,2 à 5,6. Du point de vue de leur contenu en substances nutritives, ces sols occupent une position intermédiaire entre les sols salins côtiers et les sols latéritiques.

Les travaux sur le contenu de ces sols en oligo-éléments se poursuivent. On a constaté jusqu'à présent que les alluvions récentes, les hautes terres de Chittagong et les sols salins côtiers contenaient une quantité presque identique de manganèse échangeable (de 31,2 à 36,6 ppm), alors que les sols latéritiques (alluvions anciennes rouges) sont beaucoup plus riches en manganèse échangeable (91 à 100 ppm).

Discussion

H. Brammer. I would like to comment on the pH data given by Dr. Karim for some of the soils of East Pakistan, in particular on the data given for recent alluvial soils. During the course of the Reconnaissance Soil Survey of Pakistan in the area around Dacca we have been finding considerable changes in topsoil pH between the wet season and the dry season. In soils sampled whilst still wet, after wet-season flooding, the pH was 7.0 to 7.5; a few weeks later, when dry, they may have pH values of 4.5 to 5.5. Similar changes can be found between gleyed (reduced) and oxidized portions only a few millimetres apart within the topsoil. These pH changes may be due to oxidation of sulphides, but further investigation is required. These changes in pH have important agronomic implications. Soils sampled in the dry season, or analysed after drying of the samples in the laboratory, may appear to be very acid in reaction, and management recommendations may be given accordingly. However, in the wet season, when they are used for crop production, mainly paddy, the soils may be neutral or slightly alkaline in reaction, presenting a totally different picture from the nutrient point of view. I would, therefore, recommend caution in reporting pH data in the case of alluvial soils subject to alternate flooding and drying out.

A. Q. M. B. Karim. The pH range for a soil has been mentioned instead of giving one pH value for a given soil. The pH change due to climatic differences generally remains within the range shown in the paper with a variation of 0.2 to 0.3 pH units. Such values for pH, I think, may be mentioned without giving any wrong impression about the soil property.

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Morphology, genesis and occurrence of acid sulphate soils (cat-clays) in deltas of the humid tropics

F. R. Moormann

INTRODUCTION

Acid sulphate soils are by no means restricted to the humid tropics, they have been described and studied in the temperate regions, more particularly in the Netherlands, since the latter half of the nineteenth century. Nor are sulphate soils entirely restricted to deltaic areas; they are known to occur—although to a very limited extent—in inland areas. The largest extent of these soils, however, occurs in the deltas of the humid tropics and therefore merits to be discussed in the framework of this symposium.

DEFINITION AND MORPHOLOGY

Acid sulphate soils are soils, mostly situated in marine flood-plains, which, upon drainage and aeration, show a definite acidification due to the oxidation of sulphides (mainly pyrites, FeS_2) which leads to the formation of sulphuric acid.

The term "cat-clay" (translated from the Dutch, cf. Van der Spek, 1950) has been used mainly for the oxidized soil material in acid sulphate soils, showing straw-yellow mottlings and streaks of basic ferric sulphate. The non-oxidized soil material, which is saturated with water the year round and which does not necessarily have a low pH, has been called "mud-clay" (Edelman and Van Staveren, 1958).

Field studies reveal that the morphology of acid sulphate soils differs a great deal. A common type of profile, observed in deltas of the humid tropics is as follows:

Surface soil: approximately 25 to 50 cm. deep, blackish to dark grey-brown humic, heavy clay; mostly with reddish mottling,

Subsurface soil: reaching to depths varying from 60 to 250 cm., greyish heavy clay with numerous mottles and yellow spots and streaks of basic ferric sulphate. As observed in Thailand, the upper layers of this part of the profile may show a predominance of red mottles, with the typical yellow spots beginning below. The yellow-mottled material is cat-clay.

Subsoil: uniformly pinkish-grey-brown coloured heavy clay, waterlogged, very plastic and sticky, very soft (low bearing capacity). This material presents the non-oxidized mud-clay phase; in soil surveys in South Viet-Nam, it was commonly called "soap clay" (Pham-Huu-Anh, Moormann and Golden, 1961).

Many variations in profile morphology have been observed, of which only a few can be mentioned here. Although predominantly clayey, acid sulphate soils of intermediate or even sandy texture may be observed occasionally. The thickness and depth of the actual and potential acid layers varies considerably. The cat-clay horizon may occur only in the subsurface or subsoil with less acid materials forming the top horizons. Conversely, the subsoil of acid sulphate soils may not be acid or even calcareous, although such profiles have only been exceptionally observed in the tropics. In poorly drained areas, the whole profile may consist of mud-clay, whereas in better drained areas, no mud-clay subsoil may be present. The latter situation is observed in the occasional acid sulphate soils, found on some of the slightly elevated coastal terraces on the fringe of some deltas. The oxidized cat-clay material has, with very few exceptions, a pH below 4.5. Mostly, the pH is much lower, with, in extreme cases, values between 1 and 1.5. Quite characteristic for these soils in the tropics is the pronounced seasonal variation of pH values. During inundation in the wet season, pH values mount gradually, eventually coming close to neutral, whereas during the following dry period they drop quickly. Studies on the seasonal variation of pH values have been carried out in Sierra Leone (Tomlinson, 1957; Hart, 1957).

GENESIS

Chemical and biological processes

By no means are all details known of the process of formation of acid sulphate soils. Nor have the chemical and micro-biological aspects of the acidification, resulting from oxidation, been more than partially studied. Sufficient data are available, however, to give a general picture of the processes that occur during the formation of these soils. The following "events" or phases in the formation of acid sulphate soils may be mentioned:

1. Sulphates, present in the inundating sea-water, are reduced. The reduction of sulphates is mainly a biochemical process which will proceed in an anaerobic (waterlogged) environment where organic matter is present in quantity. The sulphate-reducing bacteria derive their energy from the oxidation of the organic matter.
2. The sulphides (including hydrogen sulphide), thus formed, react with the iron compounds, present in the soil, leading to the formation of iron monosulphide (FeS) which undergoes a change into the more stable polysulphides, chiefly pyrites (FeS_2). Since these iron-sulphur compounds are insoluble, a steady accumulation occurs in lands subject to tidal inundations. If no oxidation takes place, the process stops at this stage and the soil material thus formed is the mud-clay previously mentioned. Upon oxidation and in the absence of any considerable amount of calcium carbonate, the formation continues.
3. The sulphides are oxidized by the oxygen of the air, resulting in the formation of ferric sulphate and sulphuric acid. According to Hart (1962), the sulphides oxidize chemically so as to form elemental sulphur which then is bacterially oxidized by *Thiobacillus thio-oxidans* to form acid. The ferric sulphate formed in this process hydrolizes readily, leading, by way of several intermediate stages, to the formation of the straw-yellow basic ferric sulphate and more sulphuric acid.
4. When the sulphuric acid is not rapidly drained from the soil, it reacts strongly with clay minerals, which leads to the formation of aluminum sulphates, quite characteristic for acid sulphate soils in the tropics.

Environmental factors

In acid sulphate soils, sulphur is accumulated during the sedimentation of the soil material. The sulphur, in most cases, is provided by the sulphates—mainly calcium sulphate—present in sea-water. It follows that most acid sulphate soils are composed of brackish water or marine sediments, since river sediments almost invariably have a low sulphur content.

Accumulation of sulphur in such sediments requires the presence of sufficient organic matter. In coastal regions this condition is met with in the low-lying backswamp areas of the flat deltas, where brackish water can penetrate with the tides, inundating the land regularly, especially during the dry season when the rivers carry little water. Besides, many of the low-lying mangrove swamps along several coasts may contain enough organic matter for the process of sulphur accumulation to proceed.

In higher-lying and better drained parts of the marine plains, conditions are usually not favourable for the accumulation of sulphur and, hence for the formation of acid sulphate soils. In such parts, soil conditions are aerobic for longer periods of time. Reduction of the sulphates does not take place and they are readily washed out. Also, where an oxidizing environment prevails there is usually less organic matter present and when, moreover, the pH is high the amount of soluble iron required for the formation of iron sulphides is too low. Thus, acid sulphate soils are usually absent in the river levees, even where these are regularly flooded by sea-water, and also in the higher tidal flats. The deltas of such rivers as the Mekong in Viet-Nam and the Chao-Phya in Thailand have a wide zone along the sea in which marine, non-acid soils prevail.

The presence of calcium carbonate in the sediments does not necessarily stop accumulation of sulphur if the main conditions for such an accumulation are right. However, finely divided $CaCO_3$ interferes with the acidification process because the sulphuric acid reacts with the $CaCO_3$ to form calcium sulphate (gypsum).

If little calcium carbonate is present in the original sediment, some gypsum may be found, but the soil is predominantly acid. But where the sediment contains sufficient calcium carbonate, no acidity develops and, instead, varying quantities of gypsum are found in a near-neutral or even slightly alkaline soil mass. The quantity of gypsum, more or less well crystallized, may be very considerable. In parts of the Mae-Klong delta in Thailand, up to 25 per cent of the soil mass consists of gypsum.

The primary calcium carbonate content of marine and brackish water sediments fluctuates widely, without it being possible in many cases to explain such fluctuations (Van Beers, 1962). Apparently of great influence is the nature of river water which mixed with the sea-water during and after deposition of the sediments. In deltas of silt-rich rivers, especially those which pass through limestone areas, few acid sulphate soils are found, even though the other conditions for the formation of such soils may be optimal. Here, the brackish-water—and marine sediments—contain varying quantities of gypsum instead. If the river water comes from strongly leached areas, the effect is opposite. When such water mixes with the carbonate-rich sea-water, the calcium carbonate does not precipitate because of formation of soluble $Ca(HCO_3)_2$. Under such a régime, acid sulphate soils may be formed where one would usually not expect such soils to be present. A typical example of this was observed in one of the

smaller coastal plains of central Viet-Nam, where the low flats are composed of calcareous marine clays, whereas soil acidification and cat-clay are observed along the little streams carrying acid water directly from the surrounding hills.

OCCURRENCE

Under humid tropical conditions, environmental conditions are very much in favour of the formation of acid sulphate soils, especially because of the often low content of calcium carbonate in marine and brackish-water sediments. Hence, acid sulphate soils are found in particularly large areas along the coasts in the humid tropics (Van Beers, 1962). To be mentioned specifically for South and South-East Asia are the swampy coastal regions of Borneo and East Sumatra, as well as the delta areas of the main rivers of continental South-East Asia.

In all these areas, acid sulphate soils are present in two geomorphologic positions, e.g., in certain salt-water mangrove swamps and, much more important, in backswamp areas which are or have been influenced by brackish water. The notorious Plaine des Joncs in South Viet-Nam presents a surface of many hundreds of thousands of hectares of acid sulphate soils, some of which have a potential acidity with pH values close to 1. Acid sulphate soils may be found in other geomorphologic positions, such as river levees and even in older terraces (fossil acid sulphate soils) but such soils never occupy large surfaces.

PRACTICAL IMPLICATIONS

On the whole, acid sulphate soils show characteristics, unfavourable for agriculture. The soil acidity itself, especially if it appears in the upper layers of the soil profiles, may be harmful to plant growth. Of much more importance, however, is the toxicity of high concentrations of aluminium and/or iron, which strongly affect the growth of most cultivated crops. Further, acid sulphate soils have a low fertility level, with phosphorus especially being unavailable for the plants. Whereas many acid sulphate soils do produce a rice crop, as well as some other crops such as sugar-cane, bananas and pineapples, there are still large surfaces with too high a potential or real acidity to be cultivated under the present-day economic conditions.

Reclamation of such fallow areas and improvement of the cultivated acid sulphate soils is certainly an extremely difficult and often very costly task. Because many such soils are situated in low-lying, swampy areas, reclamation in the past often consisted of improving the general drainage of the area. The results of such measures were usually nil, and more often than not negative, because drainage led to a rapid increase of acid formation and an equally rapid drop in productivity of the area. Worse, in some cases, the acid thus formed seriously affected the productivity of neighbouring, less acid lands. Experiments in Viet-Nam on backswamp acid sulphate soils (Pham-Huu-Anh, Moormann and Golden, 1961) indicate that lime and fertilizers, used in combination, may strongly increase soil productivity. The lime prevents the occurrence of soil acidity and toxicity; the fertilizers are necessary because the fertility level of these soils is low to start with.

Yields increased from less than 400 kg. paddy to more than 1,500 kg. per hectare on experimental plots. But lime and fertilizers are costly and application on a wide scale may not be economic in tropical countries for a long time to come.

Reclamation methods of potentially acid, saline mangrove lands will greatly benefit by the researches now being carried out at the West African Rice Research Institute, Rokupr (Sierra Leone). After original failure to improve the empoldered mangrove soils by leaching and drainage alone, a new method was tried out which gave an immediate and probably permanent result.[1] In a newly empoldered area the land was dried out for four months in the dry season. Subsequently, the sea-water was allowed to return for one month to leach the acid, after which the salt was removed by the initial rains. This way, an excellent first rice crop was obtained. Further acid will certainly be formed, but the rate of formation is expected to be so slow that the acid can be removed each season by the natural rainfall.

1. Personal communication of H. D. Jordan, Director, West African Rice Research Institute.

Résumé

Morphologie, genèse et distribution des sols sulfatés acides des deltas de la zone tropicale humide (F. R. Moormann)

Quoique les sols sulfatés acides apparaissent dans d'autre régions du monde, ils prennent une vaste extension dans les plaines côtières des régions tropicales humides.

Les sols sulfatés acides se caractérisent par leur acidité en état oxydé, ainsi que par la présence des sulfates d'alumine et de fer. Ces sols sont dérivés de sédiments saumâtres, contenant des sulfates qui, en milieu réducteur et sous l'influence des matières organiques, sont transformés en sulfures, surtout de la pyrite (FeS_2).

Lorsque de tels sols sont aérés par drainage, les sulfures sont oxydés et hydratés, en formant de l'acide sulfurique. L'acide sulfurique diminue les valeurs *p*H, souvent en dessous de 3. En outre, l'acide réagit avec les minéraux argileux, en formant des sulfates d'alumine et de fer. Ces derniers provoquent la formation des taches jaunes paille, très caractéristiques pour de tels sols.

Les conditions de formation sont liées à des facteurs hydrologiques et géomorphologiques bien déterminés, ce qui explique la distribution particulière de ces sols dans les zones côtières.

La valeur agricole des sols sulfatés acides est souvent médiocre; il reste de vastes étendues non cultivées, par exemple au Sud - Viêt-nam et en Indonésie. Pour la mise en valeur, le chaulage, combiné avec l'application d'engrais est indispensable.

Discussion

V. N. Nagaraja. Mr. Moormann has rightly emphasized the importance to be attached to the occurrence of cat-clays and mud-clays and has analysed the process of their formation. A proper appreciation of these formations will lead to a scientific treatment of the soil and an economical water balance

The findings at the West African Rice Research Institute (Sierra Leone), also referred to in Mr. Van der Goor's paper, are doubtless of great value in this respect.

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II
Hydrography and hydrology
Hydrographie et hydrologie

The effect of tides, coastal currents, waves and storm surges on the natural conditions prevailing in deltas

P. Santema

INTRODUCTION

In this paper certain effects of tides, coastal currents, waves and storm surges on the natural conditions prevailing in deltas will be discussed. First some general aspects of tides, coastal currents and waves will be mentioned, and then their geomorphological and hydrological effects on the coastline with its inlets and on the interior part of the delta will be discussed. Finally, a few aspects of the incidental occurrence of the rising of the normal sea level due to storms will be mentioned.

Most of the material presented in this paper has been derived from earlier studies published in *The Waters of the Niger Delta* (The Hague, Nedeco, 1961).

TIDES

Tides are generated by forces originating from the movement of the earth and the moon, and the earth and the sun, round their common centres of gravity and the variation of the attractive forces of the moon and the sun for different places on earth. An important tidal movement is thus generated in the Antarctic oceans of the Southern Hemisphere, from where it propagates northward into other ocean basins. These basins have a tidal movement of their own also. The picture is made even more complicated by certain effects of the rotation of the earth; by the effect of the configuration of the ocean basins, which may include resonance, reflection and interference of tidal waves; and by the effect of shallowness of certain areas. A tidal wave travelling from a deep ocean into a shallow sea is subject to a certain deformation and retardation.

A tide gauge on the beach of a sea with tidal movement will record the tide as a fluctuating curve. This curve is a composition of several sinoids, each of them brought about by a different cause.

As already mentioned, the fundamental causes are the moon and the sun, each of them being responsible for a set of diurnal sine waves with a period of approximately 25 hours and a set of semi-diurnal sine waves with a period of about 12 ½ hours. Of the sine waves mentioned the main semi-diurnal lunar tide is dominating at most places on earth; it has a period of 12 hours and 25 minutes.

The rise and fall of the water level causes varying depths. When the water rises at sea considerable volumes of water will flow through any opening in the coastline to fill the tidal storage area and when the water falls the water will flow back to the sea again. The flood volume, the ebb volume and the total tidal volume are not fixed quantities, but they vary with the average sea level and the tidal range and with the upland discharge. The tidal currents in an opening in the coastline will accordingly be of an ever-changing strength and direction.

The moments of slack water lag behind the moments of low water (LW) and high water (HW) due to inertia forces. In the case of a river with much upland discharge this time lag at LW may be considerable. Upstream of a certain place in a river arm there will be no longer a moment of slack water as the ebb current will run throughout the whole tidal period; this point will shift in a downstream direction with increasing river discharge.

The propagation of a tidal wave in a channel varies according to such factors as the configuration of the channel and of its basin. When passing the bars, which are normally found in front of the inlets, the tide generally is already somewhat attenuated. In a deep channel with a limited drainage basin, which ends more or less funnel-like, the tide may run higher at some distance inland than at the inner side of the bar, before it decreases in the upper part. In a channel which increasingly ramificates and shallows when going upstream, the tidal wave will attenuate from the beginning. In these cases such phenomena as friction, reflection and filling and draining the tidal storage area along the channel play a part.

The depth of a channel is limited and generally decreases further inland. Friction, therefore, will have an important influence to the effect that the tidal wave will be retarded; moreover, the tidal curve, which at sea is normally more or less a sinoid, may become increasingly deformed when propagating into shallower water. In the case of shallow rivers with a relatively large tidal range the tidal wave finally may take the form of a bore.

Another cause of deformation of the tidal curve may be reflection. As the length of a channel with a certain profile is limited, the tidal wave will be subject to reflection; this causes a return wave which is superimposed on the original one.

Deformation of sinoidal tidal curves is also effected by a rather sudden increase of the storage basin at a certain level.

The propagation of tidal waves from the coastal area into the interior strongly affects the currents. These currents, on the other hand, help to determine the configuration of the channels; that is one of the conditions by which the propagation of the tidal wave is affected in turn. A strong deformation of the tidal wave may have an important influence on the sediment transport by the tidal currents to the effect that under certain circumstances the direction of the resulting sediment transport may be reversed from seaward to inland.

CURRENTS

Currents in the coastal area can have various origins, such as: variation in density due to differences in temperature, sediment load or salinity; transport of water by wind waves; variation in water level due to tidal waves, variation in air pressure and surface friction by wind; surface friction by wind directly. The currents thus originated will be further affected by the bottom configuration and friction and the Coriolis force. According to their origin the currents may be incidental or systematic, periodic or permanent, and so will be their effects in the delta.

The effect of two currents with the same average magnitude and direction may be completely different according to the distribution of the magnitude and direction as a function of the depth below the surface, a distribution which depends on the origin of the currents and the configuration of the basin.

If the river debouches into a sea with salt water, the flow pattern in the lower portion of the river is influenced by differences in density. In the case of a tideless sea, the surface flow of fresh water may have its counterpart in an upriver flow of saline water to the effect that a so-called "salt wedge" is formed. The bed load of the river may be nearly stopped by such a salt wedge, whereas the mixing at the interface between the fresh and the salt water causes a flocculation of silt, so that in the reach of the salt wedge the bottom may be covered by a "mud blanket". In the case of a sea with tides, a well-marked similar flow pattern will normally not develop, but the flow pattern will still be influenced considerably by the differences in density.

On a normal deltaic coast provided with inlets it is possible to distinguish between the currents along the coast and those perpendicular to the coast. The longshore currents in the shallow coastal waters are usually weak; their effect on the transport of sediment, accretion and erosion will be appreciable only in the presence of wind waves, or near inlets where they are part of the tidal currents. Currents perpendicular to the coast are hardly perceptible along a regular, closed shore, but they are preponderately present in the form of tidal currents which run in and out of river mouths.

WAVES

The waves, which are of great influence on the processes of sediment transport, accretion and erosion in the coastal area, are generated by the wind blowing with a certain strength during a certain time over a certain length of sea. The waves observed at a certain place may be generated in the neighbouring sea area, or they may originate from a distant area from where they propagate in the form of swell to the place of observation. At the place of observation local wind waves and swell from various directions may be present at the same time; a wave recorder installed at this place will record, therefore, a whole spectrum of wave heights, lengths and periods.

If propagating from deep into shallow water, the waves become higher and shorter and thus steeper, until finally the point is reached when the waves break and a good deal of the wave energy is released. In shallow water the water particles describe nearly closed elliptical paths (near the bottom resulting in an oscillating movement) in such a way that the wave motion is accompanied by a forward transport of water. This transport of water towards the coast results in compensating currents parallel to the coast and return currents to the sea. If the waves approach the coast obliquely, the forward transport of water results in additional currents parallel to the coast. Irregularities in the configuration of the coastal area with related phenomena such as refraction, diffraction, etc., may bring about other compensating currents.

The water movement caused by waves strongly affects the coastal profile, the sediment transport, the accretion and the erosion in the coastal area. As these processes are very much dependent on the water depth, the whole picture of sediment sorting and transport, accretion and erosion varies with the tides.

The processes of longshore or littoral sediment transport by wave action along a straight coast have a combined effect which may be approximately described by:

$$S = k \cdot E_b \cdot \sin d_b \cdot \cos d_b.$$

In this formula S = transport of sediment parallel to the coast, k = conditioning factor, E_b = energy of the breaking waves, d_b = direction of the crests of the breaking waves with reference to the coastline. For curved and more irregularly shaped coasts the relation is a little different, in consequence of the compensating currents which may be caused by such phenomena as refraction and diffraction.

Generally speaking wind generated waves are among the most important sediment transporting agents on a coast which, together with the tides, are responsible to a large extent for the shaping of the coastline.

COASTAL ZONE OF A DELTA

The sediment load of the rivers is transported in such a way that the coarser particles remain in or near the river beds and the finer particles are carried on to be deposited away from the rivers in the delta or on the bottom of the sea. Medium-sized particles reaching the sea during floods are often moved along the beach. The deposits of medium-sized sediment along the shore are usually found in a layer as thick as the influence of the waves reaches. The upper part of these deposits takes the form of beach ridges which act as a barrier between the sea and the delta. This barrier is to a certain degree self-mending by virtue of the continuous littoral processes of sediment transport, accretion and erosion. If an occasional breach does occur, a considerable scouring power through the gap is required to overcome the healing forces. This explains why a limited number of river mouths is viable; there is only a limited amount of scouring power incorporated in a delta to maintain the openings in the coastline.

Old beach ridges, marking former coastlines, can often be recognized in the landscape by their elevation and structure. Sometimes they are a source of fresh ground water, a fact which may be reflected by the vegetation. The elevation and the availability of fresh ground water often make them the most suitable places for habitation amidst a swampy area.

As has been mentioned, the tidal currents in the lower portions of the rivers and estuaries will try to maintain openings in the coastline, whereas the sediment transport by waves and currents in the coastal area will act as a healing agent trying to restore a closed coastline. It depends on many factors which type of outlet will be established and what its dimensions will be. In general there seems to be an almost linear relationship between the cross-sectional area and the total tidal volume; the shape of the cross-section further depends on the freshwater discharge, the distribution of flow over the outlet, the sediment load of the river, the grain size of the bottom material (including "mud blankets"), the coastal currents, the wave action, the littoral drift and the seasonal variation of these factors. The configuration of the outlet area is often not stable, but follows a certain pattern of changes, which sometimes takes the form of long-period cyclic movements.

INTERIOR PART OF A DELTA

As a delta grows, the path of the main river to the sea becomes longer, the gradient diminishes and the sediment transporting capacity decreases. This means that the river bed will be raised in such a way that a natural adaptation of the longitudinal profile of the river to the new circumstances will occur. These phenomena will cause a more frequent flooding with the result that sedimentation on the flooded areas will occur at an increased rate. In the long run there will be a natural balance between the advancement of the outlets and the raising of the interior of the delta. However, the raising process originates from the coast and thence gradually moves upstream, so that the building up of the interior lags behind. This means that flooding will always be an integral part of the natural development of a delta.

There is, however, a limit to this process of lengthening of the river; one day the flood-waters will find a shorter path to the sea and scour out a new branch. It depends on the magnitude of the floods and on the other hand on the measure of resistance to be overcome as to when the new channel will be scoured and whether the development of the short-cut will meet with success or not.

The young marine deposits of a delta are very compactable and a comparatively small load will already effect considerable compaction. Such a load is normally accomplished by additional deposits, especially if the latter are not submerged. From this it follows that the subsoil of a developing delta is continuously sinking as the result of the compaction of a weighted deposit. Areas with thick layers of mud and clay are affected more than the areas with more sandy material. Thus the depressions between the river branches are affected more than the river beds to the effect that even old abandoned river and creek beds sometimes continue to be raised above the general level of the surrounding land. In areas which have been subject to subsidence for a long time, drainage may become difficult. Evaporation in dry periods then may cause a considerable increase of the salt concentration in the soil. Periodical intrusion of sea-water may also become a problem. The result of these processes is generally that the soil structure and the soil fertility deteriorate. In some deltaic areas other geological phenomena, such as tilting, sinking or upheaval, by which the level of the land relative to the mean sea level is affected, play an important role also.

Regular flooding with sediment-laden water over the whole area of a naturally developing delta is essential to counteract subsidence. Low-lying areas with insufficient drainage may be in an unfavourable position in this connexion; as the rainy season in a delta usually

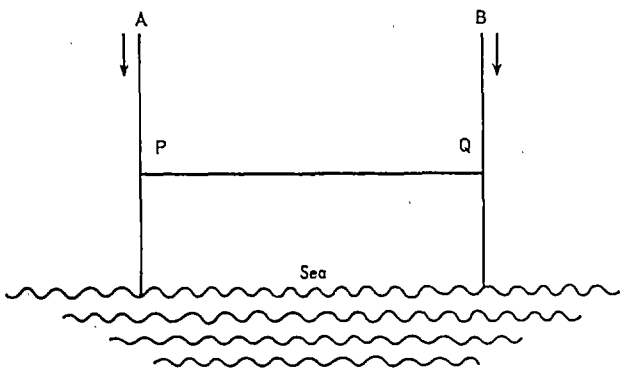

FIG. 1.

arrives earlier than the river floods, those areas are flooded with rain-water prior to the arrival of the sediment-laden flood-water which to a large degree is then denied entrance to the low-lying area.

If a more seaward-situated part of the interior of a naturally developing delta is cut off from the supply of water and sediment by the feeder river, it may eventually become a prey of the sea. The river beds, one-time arteries of the feeder system, are then used as incursion roads for sea-water. Trees die from the increasing salinity and the sinking land becomes open to the erosive forces of wind and waves. The area which is flooded by the tides expands; greater tidal volumes are required to fill the area and stronger currents will scour bigger entrances in the coastline.

At the same time, however, these processes are acting to undo the cause of the onward march of the sea. As the erosion progresses further inland and more and more of the interior becomes open to the sea, the favourable issue of any branching attempt of a nearby river becomes increasingly probable. Once such a river is captured and led into the eroded area the process will be reversed. Sedimentation will again take place, the salt water will be forced back, and the vegetation be restored. In short, the sea arm will be converted into a river arm again. A few examples may elucidate the above-mentioned situation.

First, the case is considered of a creek connecting two rivers discharging fresh water with an equal sediment load (Fig. 1). If the levels at P and Q rise and fall equally and synchronically, no current will occur and the creek will silt up. If the levels do not move synchronically currents will develop which may be strong enough to counteract siltation. A particular case would be presented if one river B offers better conditions for the propagation of the tide than another river A. If, for instance, HW in Q occurs sooner or is higher than in P, a flood current from Q to P will develop. Equally, if LW in Q occurs earlier or is lower than in P the flow will be from P to Q. This means that the path P to Q is collaborating, or rather competing, with the path P to sea; in other words there is a tendency for the river with the stronger tide to captuer the river with the weaker tide. Of the latter the part P to sea will then receive a reduced flow and may eventually silt up.

Next, the following case is considered. River A is supposed to be a river with a sediment-laden upland discharge and B is a sea arm without upland discharge and with relatively clear water. If the water levels at P and Q vary equally and synchronically, no currents will initially develop in the connecting creek PQ. But now siltation will take place in this creek in the part close to P, while erosion will occur at the opposite end. The creek will thus be opened up from Q to P. The tidal divide, which originally was situated in the middle of the creek, will now shift towards P and eventually part of the river water from A may be captured by B.

This result is the same as in the previous case where river B was supposed to be more apt for the propagation of the tide. In fact, there is every chance for a coincidence of the two suppositions; a sea arm will normally be more open to the tide than a river arm. Therefore, it is concluded that there is a tendency for a river to be captured by an adjacent river if the latter is a sea arm with a smaller sediment load and a stronger tide.

Finally, the case of a creek connecting two sea arms will be considered. Both A and B are supposed to be tidal sea arms with no appreciable sediment load. The only sediment moved is derived from the erosion of the existing banks; the concentration of this silt varies from practically nil in the sea arm, where it is regularly diluted by clear sea-water, to low near the tidal divide in the connecting creek. The little silt that moves here is concentrated near the bottom of the creek, and as velocities near the divide are so low, no turbulence will stir it up and no raising of the shallow places can be effectuated. On the other hand due to the slight current velocities no real channels can be eroded. The result is that mud flats are formed. These typical formations are very desolate areas in a delta; they are too low for habitation and too shallow for navigation, and the circulation oxygen and silt is too small for sound vegetation or fish life.

Situations do exist where the processes of sedimentation and erosion described above will not take place. If considerable quantities of silt are moving in the coastal waters, which are so shallow over extensive areas that the tidal curves are considerably influenced by this shallowness, sea arms also may be arteries for sediment transport towards the delta. In such a case quite a different set of processes of sedimentation and erosion will take place than has been described.

Generally speaking the size of a channel cross-section results as the balance between the sediment supply to a certain reach and the sediment discharge capacity out of that reach. The shape of the cross-section reflects the balance between the erosive forces

and the sedimentation together with erosion-resisting forces. The main erosion-resisting forces in the delta creeks are the cohesive power of the bed and bank material and the binding power of vegetation and peat layers. Therefore, wide and relatively shallow channels are found where the bed and banks consist of sand, whereas deep and relatively narrow channels are found where both the bed and bank material are clayey. Furthermore, the banks usually steepen where peat layers are exposed (concave banks) and shallow where young vegetation is found (accreting convex banks). In the beach ridge area the estuaries are therefore wide. In the creek reaches somewhat more inland wide waters may also be found, because the soils are erodible and because erosion is normally not compensated by sedimentation of the wash-load which moves near the bottom due to flocculation. In parts of a delta in course of active delta building the creeks are usually scoured in clay, whereas in the non-active parts extensive eroded areas may be found. More upstream in the river arms of a delta, where ample sediments are available to compensate erosion, more restricted widths may be found.

STORM SURGES

On the coast of most deltas the mean sea level may be raised incidently and temporarily due to storms, typhoons, etc., over adjacent sea areas; sometimes the deltaic coasts are affected also by storms, typhoons, etc., over sea areas more remote from where the risings of the water level propagate in the form of long-period waves. The magnitude and duration of the rise of the normal water levels in deltas due to storms, etc., depend on the cause of the rise on the deep sea, the configuration of the coastal area, the configuration of the channels in the delta and other topographic features of the delta.

Normally, storm floods, etc., will not have large-scale and lasting geomorphological and hydrological effects in the delta. Storm floods may have more lasting pedological effects in low-lying areas where the drainage is difficult; the more or less stagnant salt inundation water in such depressions, which normally are flooded only with fresh water, will cause a salinization of the soil and a deterioration of the soil structure. Storm floods are notorious, however, for their devastating effects. Exceptionally high storm-flood levels may cause great losses of human lives and property. Even in reasonably protected deltaic areas a storm-flood level exceeding all previous records may cause enormous damage. The highest water levels occur if the maximum storm effect coincides with the moment of HW during a spring tide and with a maximum upland discharge; the maximum storm effect itself may be influenced by such phenomena as resonance, squall oscillations, etc. In recent years much research has been devoted to the mathematical and experimental evaluation and forecasting of the maximum storm effect on certain coasts starting from known or forecast meteorological conditions.

Résumé

Effets des marées, des courants côtiers, des vagues et des tempêtes sur les conditions naturelles dans les deltas (P. Santema)

Ce document est consacré à l'examen de certains effets des marées, des courants côtiers, des vagues et des tempêtes sur les conditions naturelles dans les deltas. Les premiers paragraphes traitent de certains effets généraux des marées, des courants côtiers et des vagues. Leur action géomorphologique et hydrologique sur la ligne du littoral et ses anfractuosités et sur l'intérieur du delta est examinée dans les paragraphes suivants. Enfin on indique quelques effets des surélévations occasionnelles du niveau normal de la mer dues à des tempêtes.

La plus grande partie du matériel de ce document provient d'études antérieures publiées dans *The Waters of the Niger Delta*, Nedeco, La Haye, 1961.

Discussion

F. R. Fosberg. In connexion with Dr. Santema's point that there may be only a limited number of months related to the amount of water issuing, will not the pumping of fresh water, which would normally issue from the eastern channels into the western channels, cause silting up of some eastern channels?

P. Santema. The over-all geomorphological picture in the lower part of a delta is governed to a large extent by the river floods and by the tides. The use of river water for irrigation purposes will normally be restricted to the low-water season and will hardly affect the flood discharges and the tidal currents. Especially during the low-water season the use of river water for irrigation purposes, however, may have a temporary effect on the river beds concerned, including siltation, reduction of navigable depths, etc.

Hydrometeorological and tidal problems of the deltaic areas in India

V. N. Nagaraja

INTRODUCTION

Deltaic areas in the Asian and Far Eastern regions have been recognized to be of high potential value. Supporting a high density of population, the development of these areas provides at once an opportunity and a challenge to the governments concerned.

The challenge is from the forces of nature—storms and cyclones, floods and tidal encroachment. The exploitation of the potential fertility of these areas provides excellent opportunities for reclamation of new land and provision of habitation for a large number of people.

So far as the Indian peninsula is concerned the delta-building activities of river basins are mainly confined to the eastern coast, the principal drainage basins being the Ganges, the Mahanadi, the Godavari and the Krishna (Fig. 1). The rivers on the western coast are very short and steep and carry comparatively small quantities of sediment, so much so that their delta-building activity is negligible.

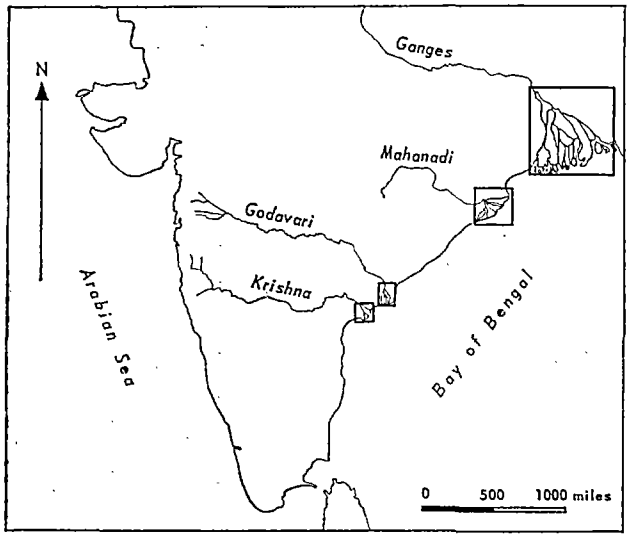

FIG. 1. Deltaic areas of India.

Of the east-flowing rivers of India, the biggest of the delta-building rivers is the Ganges. The whole of West Bengal and a great part of East Pakistan owe their existence to this great river.

Great changes took place after the sixteenth century. The Ganges moved steadily eastward, abandoning its main course through the Bhagirathi-Hooghly, thereby shifting the delta-building activity eastwards also. With this, the delta-building activity of the Ganges on the western side practically came to a standstill. This explains the fact that the deltaic areas in East Pakistan are much lower than the adjacent areas in West Bengal.

In spite of the vast quantity of silt brought down by the Ganges (estimated at approximately 450 million tons a year) the extension of the delta face has been extremely slow, mainly because of the very strong tides at the head of the Bay of Bengal which distribute the silt over a wide area. The presence of the "swatch of no ground" south of the deltaic face appears to have an influence in this process.

The Mahanadi (catchment area 51,300 sq. miles), the Godavari (catchment area 121,500 sq. miles) and the Krishna (catchment area 91,000 sq. miles) have also built up conspicuous deltas. Since these rivers bring large quantities of silt, and the tides are not as strong as in the Bay of Bengal, and as there is substantial littoral drift along the eastern coast, the rate of advance of the deltaic space is pronounced. In the case of the Mahanadi, the delta face has advanced at the rate of about 52 ft. per year.

HYDROMETEOROLOGICAL CONDITIONS

The climate in the West Bengal region is characterized by the typical monsoon, most of the rainfall occurring between June and October. The hottest months are

TABLE 1. Comparison of rainfall and temperatures of four deltas

Month	Sunderbans delta[1] (A) Temperature (°F)	Sunderbans delta[1] (A) Rainfall (in.)	Mahanadi delta[2] (B) Temperature (°F)	Mahanadi delta[2] (B) Rainfall (in.)	Godavari delta[3] (C) Temperature (°F)	Godavari delta[3] (D) Rainfall (in.)	Krishna delta[4] (E) Temperature (°F)	Krishna delta[4] (F) Rainfall (in.)
January	67	0.236	89	0.32	86.90	0.02	87.2	0.22
February	71.8	1.65	96	0.78	92.7	0.28	92.1	0.492
March	80.5	1.06	103.8	1.04	98.0	0.63	96.0	0.382
April	90.6	1.21	108	1.07	102.0	1.23	101.10	0.86
May	87	6.9	109	3.57	109.0	3.10	110.80	1.97
June	85.6	10.63	106.2	9.95	106.8	5.22	106.90	4.7
July	84	10.9	96.2	12.89	97.90	9.66	110.60	7.8
August	83.5	12.15	93.9	13.40	95.70	7.50	97.20	7.15
September	84	11.3	94.3	9.76	95.20	5.96	95.90	5.81
October	81.5	5.6	94	5.34	93.40	6.49	93.80	5.11
November	74	1.5	89.9	1.62	87.30	2.13	88.40	2.94
December	67	0.2	85.6	0.23	83.90	0.34	85.60	0.22

1. A = Calcutta.
2. B = Cuttack
3. C = Kakinada; D = Dhawlaiswaram.
4. E = Masaulipatam; F = Vijayawada.

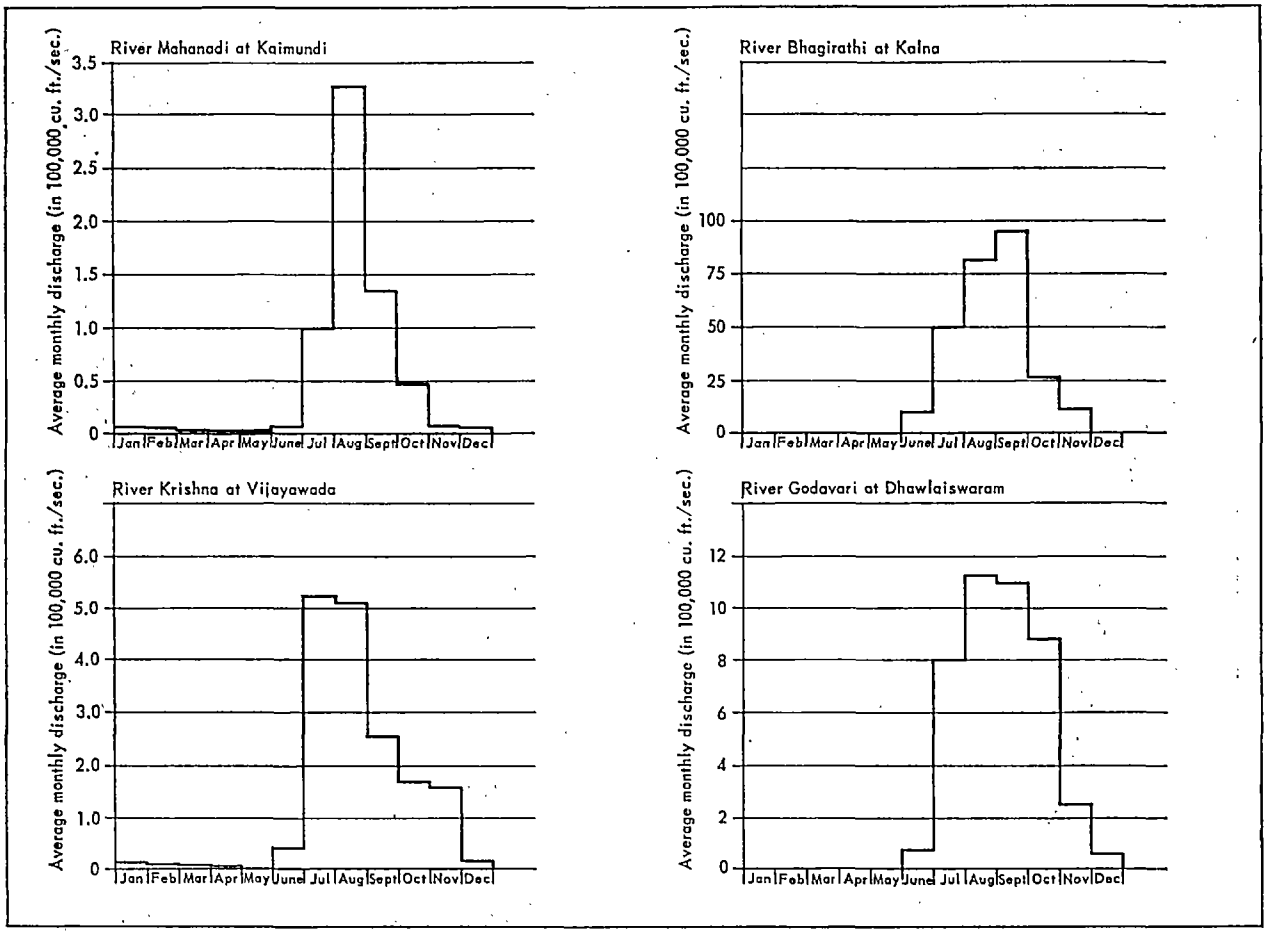

FIG. 2. Typical hydrographs.

April and May, and the wettest months are July and August.

In the Godavari and Krishna deltas, the hottest month is May and July-August is the wettest period. A comparison of the rainfall and temperatures of the four deltas typified by Calcutta (Ganges delta), Cuttack (Mahanadi delta), Dhawlaiswaram and Kakinada (Godavari delta) and Vijayawada (Krishna delta) is given in Table 1. The maximum run-off occurs during the monsoon period (July-September) (Fig. 2) after which the flow dwindles down to very low values (88 per cent of the rainfall in Godavari occurs during the south-west monsoon season). The Krishna basin is influenced by both south-west and north-east monsoons, but the influence of the former is spread over a longer period than that of the latter. The lower reaches of Godavari are under the influence of south-west monsoons.

THE FLOOD PROBLEM

Since the monsoon period is confined to about four months in the year (July to October) more than 80 per cent of the rainfall occurs within this period. In West Bengal where most of the rivers have become moribund, floods are an annual feature and large areas are affected every year. The principal rivers have been mostly embanked, but since these embankments are old and have not been always properly maintained, breaches take place and considerable property is destroyed. Because of the high intensity of population, it has not been possible to provide for specific detention basins and the topography does not permit purposeful storage reservoirs. The West Bengal Government is greatly concerned over this problem and has evolved a comprehensive scheme of improvement of drainage, providing protective embankments, etc. Arrangements are also being made for a flood-warning system so that serious damage on account of unavoidable floods is minimised.

In the deltaic areas of Mahanadi, Godavari and Krishna a number of drainage channels have been embanked and the coastal areas are also protected by embankments. Excessive floods occur only for a short period in the area and elaborate arrangements have been made for patrolling the embankments and taking prompt action for the prevention of breaches. Protection works by way of boulder revetment, plantation of special species of grass, etc., are resorted to in areas subjected to erosion. Owing to aggradation of the river, the high flood level is known to have accentuated in recent times and plans are being made for raising some of the embankments and strengthening others. It is hoped that, with the storage projects which are coming up in the upper catchments of these rivers, river aggradation will diminish and the existing protection works will prove adequate for protecting the areas now subjected to floods.

TIDAL INFLUENCES AND STORM SURGES

As mentioned earlier, the tides at the head of the Bay of Bengal are very strong, the range varying from about 6 ft. in the neap tide to about 16 ft. in the spring tide. This range, however, reduces towards the south, along the eastern coast of India, as may be seen from Table 2. This tidal activity is reflected all along the coastline and particularly in the Bengal region. It provides the necessary depths for extensive navigation. The Hooghly, Matla and other estuaries of West Bengal owe their existence to these tidal influences. Tidal influences are comparatively small in the deltas of Mahanadi, Godavari and Krishna and affect a very narrow strip of land along the coast.

TABLE 2. Tidal ranges (in feet)

Location	Spring tide	Neap tide
Saugor (head of the Bay of Bengal)	16	6
Paradip port (below Mahanadi mouth)	7	4
Vizagapatam	6	3 ½
Madras	4	2

With the fall of the barometric pressure in March, there is a rise in the mean tide level at the head of the bay and the sea becomes rough with the onset of the monsoon (July). Heavy storms and surges occur at this time of the year; in connexion with the proposed deep seaport at Haldia at the mouth of the Hooghly an analysis has been made of the available data, which unfortunately is limited. However, they provide some basis for assessing the effects of these storm surges on high-water and low-water levels. The cyclones of 1854, 1901 and 1942 have all produced surges exceeding 3 ½ feet above the predicted high water level.

The cyclones of 1854 and 1942 had the severest recorded effect on the River Hooghly, as seen from the data in Table 3.

TABLE 3. Effect of cyclones on the Hooghly

Year	Maximum high-water level	Height of surge
1854	Unknown	It is reported that a surge of 20 ft. occurred in the estuary
1901	22 ft. 9 in.	4 ft. 6 in.
1942 (October)	27 ft. 3 in. at Saugor[1]	About 10 ft. above predicted level

1. Approximate figures as gauge was destroyed.

Apart from the above, many other storm surges have struck the Sunderbans coast. As a matter of fact any cyclone following a northern track is liable to produce a surge to the east of its centre. Table 4 lists all cyclones during the 50 years, 1907-56.

There have also been some cyclones which did not affect the Hooghly estuary but struck other areas. For instance, the cyclone of 1885 did not affect the Hooghly but affected areas near False Point, south of the Hooghly estuary. This produced a measured wave height of 22 ft. above mean sea level.

TABLE 4. All cyclonic storms which crossed the Sunderbans coast (West Bengal portion) during the 50 years from 1907 to 1956

Year	Period during which storm affected coastal area	Position where storm crossed the coast	Maximum wind speed recorded by ship or observatory (m.p.h.)	Remarks regarding tide, swell, etc.
1907	17 to 19 June	East of Saugor Island	59	—
	24 and 25 June	East of Saugor Island	59	—
1909	17 and 18 October	East of Saugor Island	78 (light vessel)	172 human beings and 5,000 cattle perished
1912	5 and 6 September	East of Saugor Island	50	—
1913	23 to 25 July	Near Saugor Island	78	—
	30 and 31 July	East of Saugor Island	78	—
1916	21 and 22 September	East of Saugor Island	42 (ship)	—
	9 and 10 November	West of Saugor Island	50 (Midnapore)	—
1917	3 May	West of Saugor Island	78	—
	30 and 31 October	Near Saugor Island	28	—
1919	24 and 25 September	East of Saugor Island	78	In its track the devastation was enormous; many huts collapsed
1920	21 to 23 July	East of Saugor Island	50	
1921	26 and 27 July	East of Saugor Island	42 (ship)	Rough sea
1925	27 and 28 June	West of Saugor Island	50 (Sandheads)	High sea and heavy swell
1927	28 and 29 July	East of Saugor Island	78	High sea and heavy swell (mountainous sea and heavy swell)
1928	18 to 20 July	East of Saugor Island	78	—
1929	15 to 17 July	Near Saugor Island	35	Rough sea and heavy swell
1932	23 and 24 May	Near Saugor Island	78 (ship)	—
1933	20 and 21 September	Near Saugor Island	35 (ship)	High sea and heavy swell
1935	8 and 9 July	Near Saugor Island	78 (ship near Saugor Island)	High sea and heavy swell
1936	26 to 28 May	Near Saugor Island	70 (Saugor Island)	—
1937	28 and 29 September	East of Saugor Island	78 (ship)	Very rough sea and heavy swell
			50 (Saugor Island	
1940	30 June and 1 July	East of Saugor Island	50 (Saugor Island)	Floods and damage to property
	7 and 8 July	East of Saugor Island	50 (Saugor Island)	Floods and damage to property
	2 and 3 August	East of Saugor Island	50 (Saugor Island)	—
	21 and 22 October	East of Saugor Island	50 (Saugor Island)	—
1941	9 and 10 July	West of Saugor Island	50	—
	8 and 9 August	West of Saugor Island	50	—
1942	9 and 10 July	East of Saugor Island	50 (Saugor) 50 (Calcutta)	—
	16 and 17 October	West of Saugor Island	140 (Sandheads) 100 (Saugor Island) 68 (Calcutta)	Rough sea and tidal wave height 16 ft.[1]
1945	1 and 2 July	West of Saugor Island	50	—
1946	4 and 5 October	East of Saugor Island	50	—
1950	10 and 11 June	East of Saugor Island	59 (Sandheads) 54 (Saugor Island)	—
1952	4 July	West of Saugor Island	—	—
1956	30 May to 2 June	West of Saugor Island	—	—

1. Precise information in respect of height of tidal wave is not available.

LITTORAL CURRENTS

Significant littoral movements have been observed at Madras and Vizagapatam on the east coast of India, as much as 1 million tons of silt moving annually from south to north, most of which is contributed by the delta-building rivers of the eastern coast. Due to the peculiar coastal configuration, however, there is no evidence of littoral movement at the mouth of the Hooghly and its adjacent estuaries. For instance, velocity observations made at the outer estuary of the Hooghly showed predominant north-south currents only. This is attributed to the protrusion at and a sudden recession of the coastline north of False Point. The existence of the "swatch of no ground" is also believed to be a deterrent factor against littoral drift into the estuary.

SEA ENCROACHMENT AND SALINE INTRUSION

The fertility of the deltas has for ages attracted the attention of enterprising people who set about reclaiming lands by means of marginal embankments and cultivating them. These works were neither planned on a scientific basis nor constructed with adequate strength so that they now present a serious problem of maintenance.

In the Sunderbans, in particular, considerable areas have been prematurely reclaimed by diking, the land levels being 5-6 ft. below the mean tide level. This obviously interfered with the natural delta-building activity of the rivers with the result that the river channels started silting up. The embankments were not strong enough to withstand the storms and surges and breaches became common, with large areas being flooded with saline water. Maintenance of these ill-planned and weak embankments has been one of the most difficult tasks imposed on the State.

In the case of the other eastern deltas, however, the problem is far less serious and is being dealt with adequately without much trouble.

Realizing the perpetual problems arising out of premature reclamation, it is now laid down for the Sunderbans area that no land should be reclaimed for cultivation unless it has been built up to a level midway between the high-water spring- and high-water neap-tide levels.

PROGRAMME OF THE SUNDERBANS IN WEST BENGAL

Extensive investigations are being carried out to enable the State to prepare an over-all plan of development of the Sunderbans delta. These investigations cover a network of observation zones and the data include tide levels, velocities and discharges, hydrographic survey data, freshwater flow, soil and silt, etc. It is realized that for any effective planning certain river inlets may have to be closed, but before undertaking any such work, care has to be taken that: (a) the work can withstand the forces of nature-tides and surges; (b) the drainage system is not adversely affected; (c) the measures adopted for any one channel would not adversely affect adjacent interconnected channels; (d) a balanced local irrigation-cum-drainage system is possible.

It is felt that fresh water for the purpose of irrigation from outside is neither necessary nor desirable under the deltaic conditions prevailing in the Sunderbans. As a matter of fact, this is in line with experiences in America and elsewhere, where it has been found that in order to preserve the fertility and infiltration characteristics, a rotation of wetting and drying is beneficial. This is all the more desirable in deltaic areas which suffer from inundations year in and year out. The conventional mode of irrigation is, therefore, restricted in West Bengal to a few patches remote from the coastal region, but is ruled out altogether for the Sunderbans area. A judicious temporary storing of the monsoon water supply in one part of the area for utilization in other parts, would certainly fully meet the water requirements for irrigation. A judicious rotation of crops would further help in this necessary alternation of wetting and drying for the preservation of soil fertility.

A plan is envisaged to develop the Sunderbans in stages. The first phase comprises the following features: (a) providing protection to the mainland on the north of Namkhana Creek, bounded by Calchara or Moriganga on the east (135 sq. miles); (b) protection to lands beyond Namkhana Creek, and lying between Pitt's Creek and Saptamukhi; (c) protecting Mahasani Island between Barakhali and Pitt's Creek; (d) protecting Saugor Island.

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Résumé

Problèmes posés par l'action des facteurs hydro-météorologiques et de la marée dans les zones deltaïques de l'Inde (V. N. Nagaraja)

1. Il est reconnu que l'exploitation des zones deltaïques d'Asie et d'Extrême-Orient pourrait donner d'excellents résultats. La mise en valeur de ces zones, qui peuvent nourrir une population très dense, soulève de graves difficultés; mais elle offre en même temps d'intéressantes possibilités aux gouvernements des pays considérés.

Les difficultés proviennent des tempêtes et des cyclones, des ingressions de la mer, de la salinisation et des inondations. Les possibilités offertes sont les suivantes : tirer parti de la fertilité des régions deltaïques; mettre en valeur et rendre habitables des sols régénérés et asséchés.

2. La fréquence d'inondations dévastatrices, l'excès d'arrosage, la saturation du sol par l'eau, le paludisme, la salinisation des terres par suite de modifications chimiques ou des ingressions de la mer — tels sont quelques-uns des maux auxquels les régions deltaïques sont habituellement exposées, et dont ont toujours souffert le Bengale-Occidental, le Pakistan-Oriental et les différents deltas de la côte orientale de l'Inde. Les gouvernements intéressés sont résolus à maîtriser les forces naturelles contre lesquelles les hommes ont à lutter dans ces régions.

3. On a observé à Madras et à Vizag, sur la côte orientale de l'Inde, d'importants mouvements de terrain dus au déplacement vers le nord d'un bon million de tonnes de limon provenant essentiellement des apports de trois grands fleuves (Krishna, Godavari et Mahanadi). Cependant, en raison de la configuration du littoral, il ne se produit pas de mouvements de ce genre à l'embouchure de l'Hugli et dans les estuaires voisins.

4. L'amplitude de la marée décroît du nord au sud le long de la côte orientale de l'Inde. Tandis que certaines régions du Bengale doivent être protégées contre l'action de la marée, les deltas situés plus au nord sont exposés à des inondations au moment des crues fluviales. Les fleuves qui aboutissent à ces deltas sont bordés de digues qui doivent être surélevées à mesure que le lit s'envase. Ces digues doivent être surveillées et entretenues chaque année au moment des crues; autrement, il s'y ouvre des brèches, ce qui aggrave les inondations et accélère l'alluvionnement.

5. Le Bengale-Occidental, dont le sol est constitué par les limons provenant du Gange, a beaucoup souffert de la modification que le cours principal du fleuve a subie, peu après le XVIe siècle, dans la région appelée Bagirathi-Hugli. Cette modification a provoqué l'apparition de vastes zones marécageuses où sévit le paludisme, et qui sont à la fois mal drainées et sujettes aux inondations.

On a déjà récupéré dans le Sonderband (bordure méridionale du Bengale-Occidental) quelque 3 620 km² de terre; mais ces travaux n'ont pas été organisés de façon systématique et scientifique. Les digues qui visent à empêcher les ingressions de la mer sont mal conçues et mal orientées; des brèches s'y produisent pendant les fortes tempêtes, ce qui crée des dangers pour les terres comme pour la population. L'application d'un plan de mise en valeur du Sonderband fera beaucoup pour améliorer le sort des nombreux réfugiés qui se sont fixés au Bengale-Occidental, et pour augmenter la production alimentaire de la région.

Afin d'adapter l'action des forces naturelles aux besoins humains, on a établi un programme de mise en valeur du Sonderband sur la base des principes suivants :

a) La mise en valeur du sol doit être entreprise seulement là où des deltas se sont formés naturellement.
b) Des études du milieu de grande envergure doivent précéder l'élaboration des plans d'ensemble.
c) Les anciens cours d'eau et chenaux doivent être rétablis pour servir à des fins multiples : drainage, irrigation, navigation, pisciculture, développement industriel, etc.
d) L'aménagement d'un cours d'eau (ou d'un chenal) donné ne doit pas avoir des effets défavorables sur le cours d'eau (ou le chenal) voisin.
e) En vue, d'une part, de drainer le sol et, de l'autre, d'obtenir des récoltes régulières grâce à une irrigation assurée à des époques appropriées, le meilleur système consiste, semble-t-il, à créer dans le Sonderband une série de polders isolés les uns des autres.
f) Le programme de mise en valeur devra être exécuté avec prudence et par étapes, et il conviendra de tenir compte, à chaque étape, de l'expérience acquise.

Discussion

V. N. NAGARAJA. Replying to the speaker seeking elaboration of the first sentence of the second paragraph under the heading "Programme of the Sunderbans in West Bengal": It is known that the important factor conditioning the area in question is frequent inundation and hence the problems of drainage and maintenance of soil fertility assume great importance. Under such conditions the most purposeful technique would be to divide the area into suitable polders and into a self-contained water management, drainage and irrigation system.

F. R. FOSBERG. What is meant by the term "swatch of no ground"?

V. N. NAGARAJA. The term "swatch of no ground" refers to a narrow zone at the apex of the Bay of Bengal and off the Sunderbans delta which is characterized by its exceptional depth.

The meteorological problems of the deltaic flood-plains of East Pakistan

Sibte Nabi Naqvi

The whole of East Pakistan outside the district of Chittagong and Chittagong hill tracts is situated in the flood-plains of the Ganges, Brahmaputra, Meghna, Tista and Surma rivers, but the present study deals primarily with flood-plains of the proper delta region, roughly triangular in shape, covering an area of about 15,504 sq. miles and distributed over six districts as follows: Kushtia (1,372 sq. miles), Faridpur (2,694), Jessore (2,547), Khulna (4,652), Patuakhali (1,704), Barisal (2,535).

The districts of Noakhali (1,855 sq. miles), Comilla (2,593 sq. miles), Dacca (2,883 sq. miles) and Pabna (1,877 sq. miles), though not strictly forming a part of the delta, are not very much different in so far as the meteorological problems are concerned.

In this area the surface meteorological observatories at Jessore and Narayanganj were established in 1867 and now have climatic data of about a hundred years. The observatories at Faridpur, Barisal, Noakhali and Comilla were started in 1883, at Pabna in 1905 and at Khulna and Satkhira in 1921. The pilot balloon observatory at Dacca has existed since 1949. This network has been supplemented by pilot balloon observatories at Jessore, Barisal and Ishurdi in the last decade. The existing density is thus about one observatory per 2,746 sq. miles which, according to normal standards, is a quite satisfactory network. The present study, which brought out some very interesting peculiarities, makes the strengthening of this network highly desirable. This is therefore the first climatological requirement of the deltaic flood-plains of East Pakistan.

This study was originally intended to extend the previous work of the author on problems of land use in the tropically humid region of East Pakistan and to discuss the economic consequences of the severe weather phenomena, like the cyclonic storms and the "nor'wester" squalls experienced in this region. The preliminary examination of the temperature, humidity and rainfall data of the deltaic stations, however, revealed some interesting features which are discussed in this paper.

The *Climatological Atlas of India* by Sir John Eliot (1906) and the *Climatological Atlas for the Meteorologists and Airmen* published by the Meteorological Department of British India in 1943 are so far the most generally available sources of climatic maps of the region. The isothermal charts of maximum, minimum and mean temperatures and isopleths of diurnal range of temperature included in this paper, however, present a picture different from that obtained in the atlases referred to above. The characteristics of the deltaic flood-plains of East Pakistan as brought out by these charts are sumarized in Table 1.

A study of these characteristics shows that there are the following three distinct seasons in the delta: winter season from November to February, summer season from March to May, monsoon season from June to October.

The charts for (a) mean daily maximum temperature; (b) mean daily minimum temperature; (c) mean daily temperature; and (d) the diurnal range of temperature for January, April and July representing the typical conditions in each season are given in Figures 1, 2 and 3 respectively. Figure 4 shows the mean annual conditions in respect of the four elements mentioned above.

It will be seen from Table 1 that, although the variations of different thermal elements from month to month and during the year are not large, they are more or less uniform in each season and significantly different in different seasons.

In the winter season when the continental air mass extends to the Bay of Bengal, the range of temperature in this air mass is 15° to 20° F. overhead of the Bay of Bengal and 24° to 29° F. over Kushtia and Jessore districts. In summer the range of temperature is 11° to 12° F. over sea areas and 20° to 28° F. over Rajshahi, Kushtia and Pabna districts. In the monsoon period the range of temperature in the pure maritime air mass over the sea is 8° to 10° F. and not more than 15° F. over the land. A notable feature, however, in practically all the months is that the isopleths of the ranges of

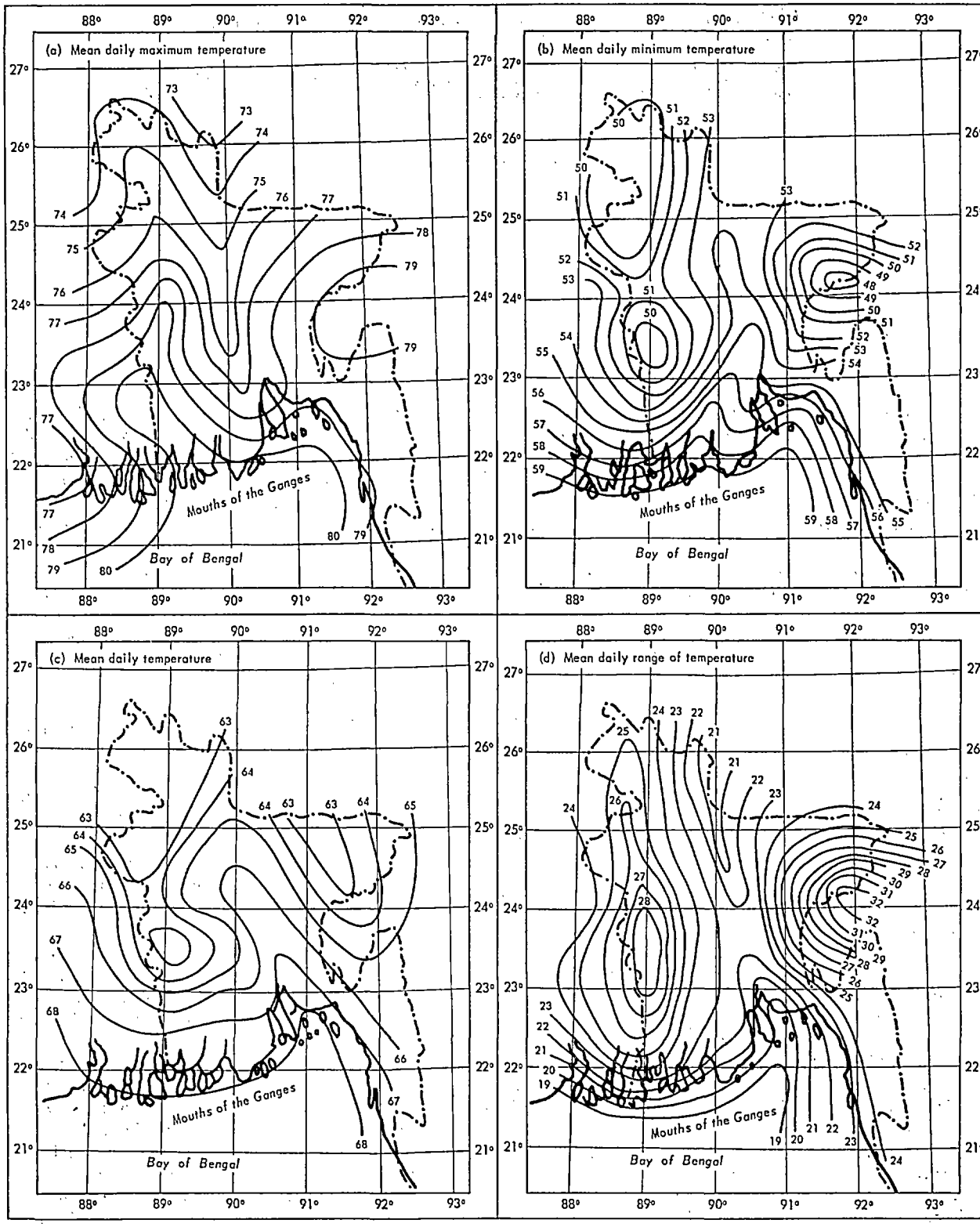

FIG. 1. Thermal conditions in East Pakistan. Winter season (January).

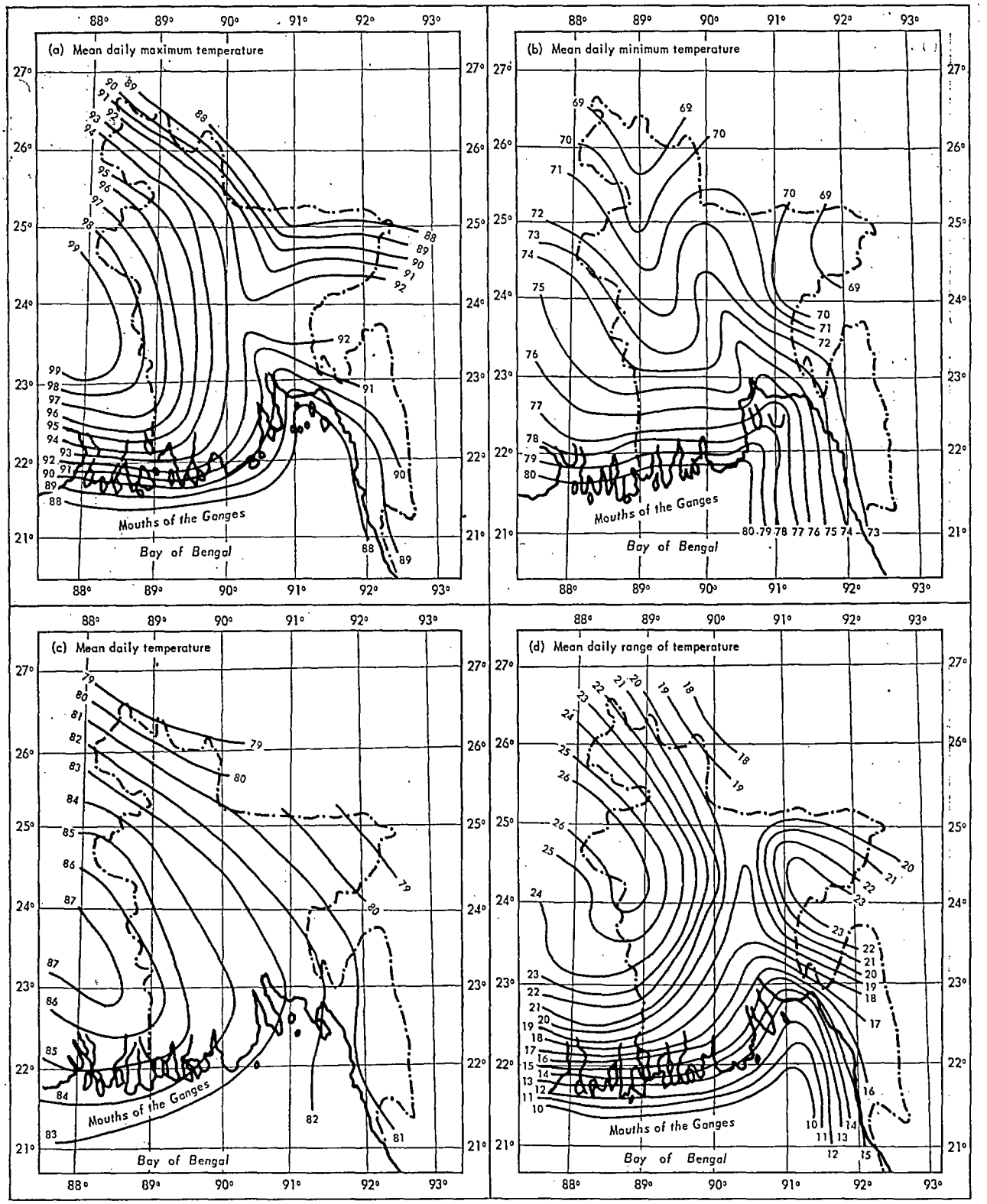

FIG. 2. Thermal conditions in East Pakistan. Summer season (April).

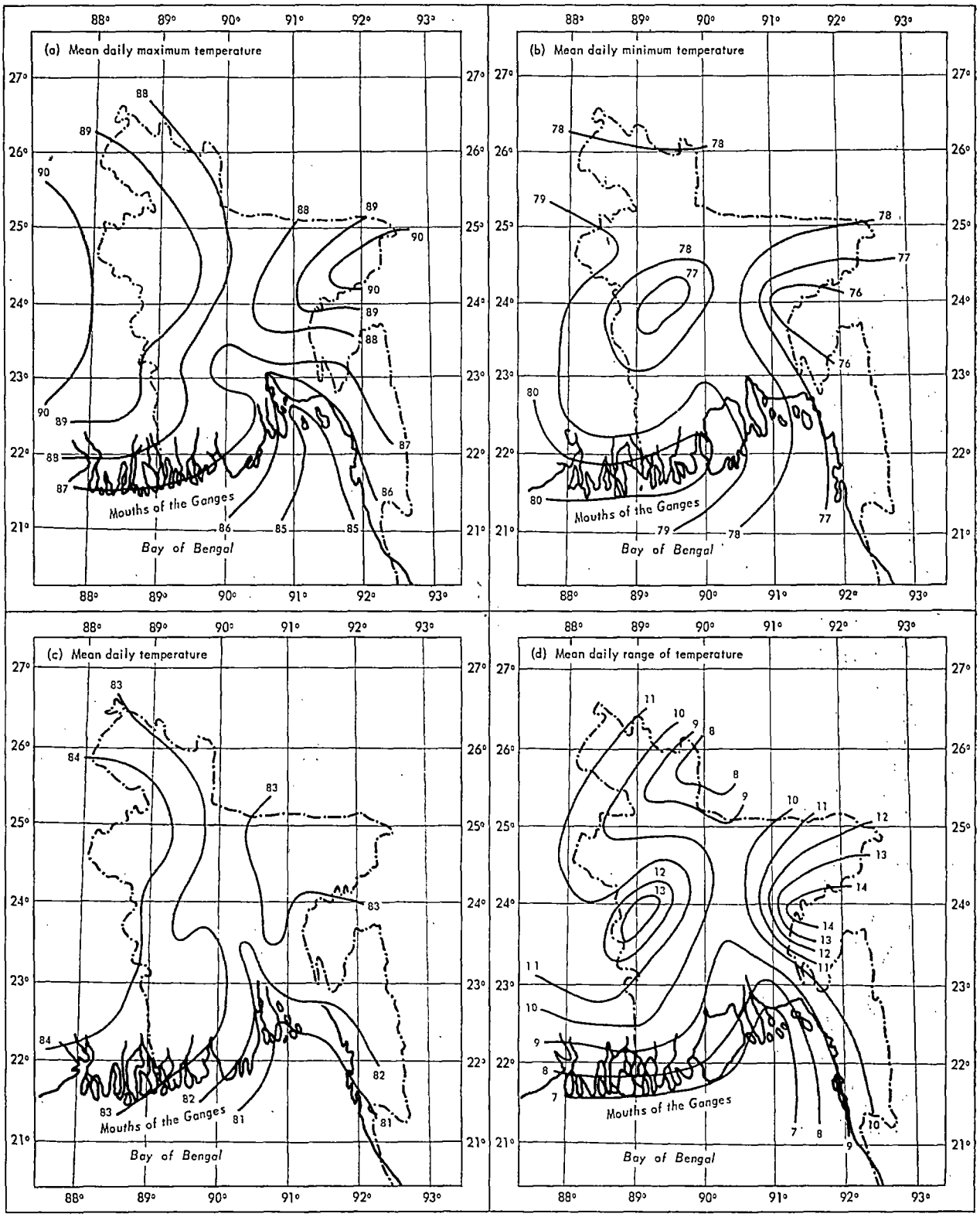

Fig. 3. Thermal conditions in East Pakistan. Monsoon season (July).

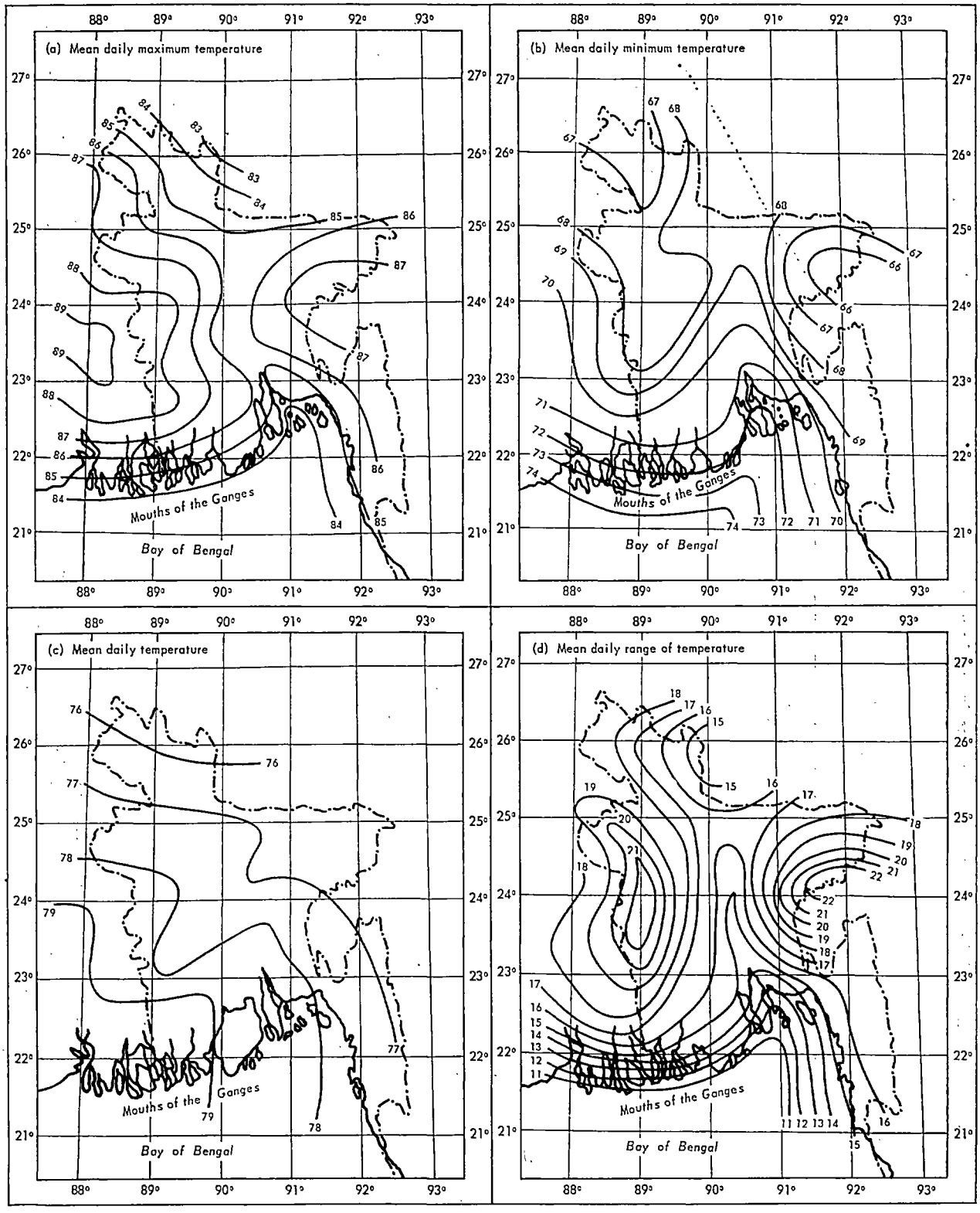

FIG. 4. Thermal conditions in East Pakistan. Annual.

TABLE 1. Temperature characteristics of the delta[1] in different months during the year

Month	On mean temperature chart				On maximum temperature chart				On minimum temperature chart				On mean daily range of temperature chart			
	Highest		Lowest		Highest		Lowest		Highest		Lowest		Highest		Lowest	
	Area	Temp. (°F.) greater than	Area	Temp. (°F.) less than	Area	Temp. (°F.) greater than	Area	Temp. (°F.) less than	Area	Temp. (°F.) greater than	Area	Temp. (°F.) less than	Area	Temp. (°F.) greater than	Area	Temp. (°F.) less than
November	20, 21	75	7	73	5, 6, 7, 8, 19	85	1, 2, 20, 21	82 84	20, 21	67	6, 7	61	7	24	20, 21	15
December	20, 21; penetrates to 17	69	7	65	7	80	21	77	20, 21	59	7	52	7	28	20, 21	17
January	20, 21	68	6, 7	64	8, 21	80	9	76	20, 21	59	7	50	7	29	21	20
February	21	73	6	68	8, 21	84	9	80	21	64	4, 5, 6	55	6, 7	27	20, 21	19
March	8	81	12, 1, 2	76	8	93	20, 21; penetrates to 17	88	21	74	4	63	5, 6	28	21	12
April	8	86	19	80	3, 6, 7	96	20, 21	88	21	79	1, 2	70	3, 5, 6	25	20, 21	12
May	8	86	19	81	3, 6	96	20, 21	89	21	81	18, 19	72	3, 5, 6	20	20, 21	11
June	7	86	12, 20	82	7	96	20, 21	86	8 near 21	80	18, 19	75	6	18	20, 21	9
July	3, 6	84	20	81	3, 6, 8	88	20	85	Saugor Island	80	12	76	6	13	20, 21	8
August	3, Burdwan	84	20	81	3, 5, 6, 7	89	20, 21	85	Saugor Island	79	12	76	6	13	20, 21	8
September	Burdwan	84	20	81	3, 7	90	20, 21	87	Saugor Island and 8	79	12	76	6	14	20, 21	8
October	8 to 13 and 15	81	Rest	81	6	90	20, 21	87	Saugor Island and 8, 10, 11	76	3, 6	70	6	17	20, 21	10

1. The numbers used for different districts in the column for area are as follows:

1 Dinajpur
2 Rangpur
3 Rajshahi
4 Bogra
5 Pabna
6 Kushtia
7 Jessore
8 Khulna
9 Faridpur
10 Barisal
11 Patuakhali
12 Chittagong
13 Noakhali
14 Comilla
15 Dacca
16 Tangail
17 Nasirabad
18 Quaidabad
19 Sylhet
20 Bay of Bengal, along Chittagong coast
21 Bay of Bengal, south of Sundarbans

temperature over the sea in different months extend northwards along the Brahmaputra valley up to the Nasirabad district and divide East Pakistan into three parts: (a) to the west of longitude 90° E.; (b) to the east of longitude 90.5° E.; and (c) a narrow strip of about half a degree in width, separating the first two. The maritime effect extends northwards in this strip and separates the dominantly continental air to the east and west of the strip, particularly in the summer months of March to May. This is the season in which the tornadic nor'wester squalls occur. The part played by this phenomenon in the formation of the tornadic nor'wester squalls is a problem to be investigated.

In Figure 5 isopleths of the total number of thunderstorms in the months of March to May have been drawn on the map showing the rivers of East Pakistan. It will be noted that both the narrow belt from the Meghna estuary to Nasirabad district, which continues to remain under a more or less uniform maritime air mass, and the Jessore district, which remains under a typical continental air mass, have much fewer thunderstorms than the border areas at Krishnagar in the west and Comilla and Narayanganj districts in the east where the maritime and continental air masses come together and produce conditions favourable for instability and consequent thunderstorms. The maximum thundersquall activity on both sides of the strip is in the neighbourhood of the Tropic of Cancer where

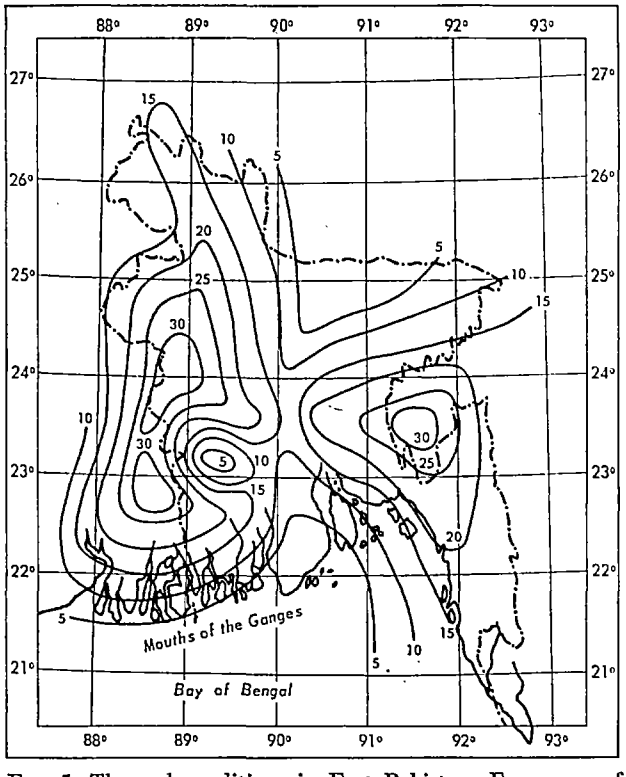

FIG. 5. Thermal conditions in East Pakistan. Frequency of nor'westers during summer (March to May).

apparently the exchange of energy between the tropics and extra-tropics takes place. This is, however, an unsolved problem which has been engaging the attention of meteorologists in the Indo-Pakistan subcontinent for several decades. It requires much further study before any definite statement can be made. The indications on the present charts may, however, point to the solution.

Another meteorological problem of the deltaic flood-plains of East Pakistan is the incidence of tropical cyclonic storms and storm surges which cause heavy losses of life and property in the region. Their unusually high frequency of occurrence since October 1960 has been most disturbing. Naqvi (1962) has found that there is a pronounced periodicity in storminess of the north Indian Ocean and it consists of several components of 3 to 5 years, 10 to 13 years, 18 to 23 years and 49 to 52 years. The period of maximum storminess has already passed and we may expect fewer storms and depressions in the 1970s.

A second problem which is of great importance for land use is that of evaporation and water balance. Evaporation observations have been taken at Cox's Bazar and Chittagong for some years. W. U. Khan (1964) has analysed the results of these observations and Naqvi (1956) has discussed these problems in his paper on *Humid Tropics Research. A Survey of Problems of East Pakistan and their Possible Solutions.* The results of that study are reproduced in Figure 6. The water surplus and deficiency calculated on the basis of Thornthwaite's formula is given in Table 2 in which moisture index and the classification of climate according to his system and that of Köppen has also been indicated. It is rather confusing when we find that with the same data the climate is termed in two different ways in the two systems and if we consider the other systems of classification the confusion becomes worse. In view of this it is considered most suitable to use the climatological data for estimating the climatic potential of the region instead of spending time on classification. This can be done easily from the comprehensive climatological normals that are available for the stations mentioned in the area. These data can be used directly for rationalization of the forest wealth of the Sunderbans on the basis of Table 3 in which the forest trees which can be grown under the climatic conditions obtained in different parts of East Pakistan are given.

Similar tables can be prepared for agricultural crops and improvements in food resources and forest wealth can be effected expeditiously.

A third and very important problem is that of the great fluctuation in sea level in the winter and the monsoon period. In the winter months when the northerly and north-easterly winds dominate the sea level in the north Bay of Bengal is lowest. But in the monsoon period persistent southerly and south-westerly monsoon winds cause huge piling up of sea-water in the north and the sea level rises by 5 to 7 ft. This happens in

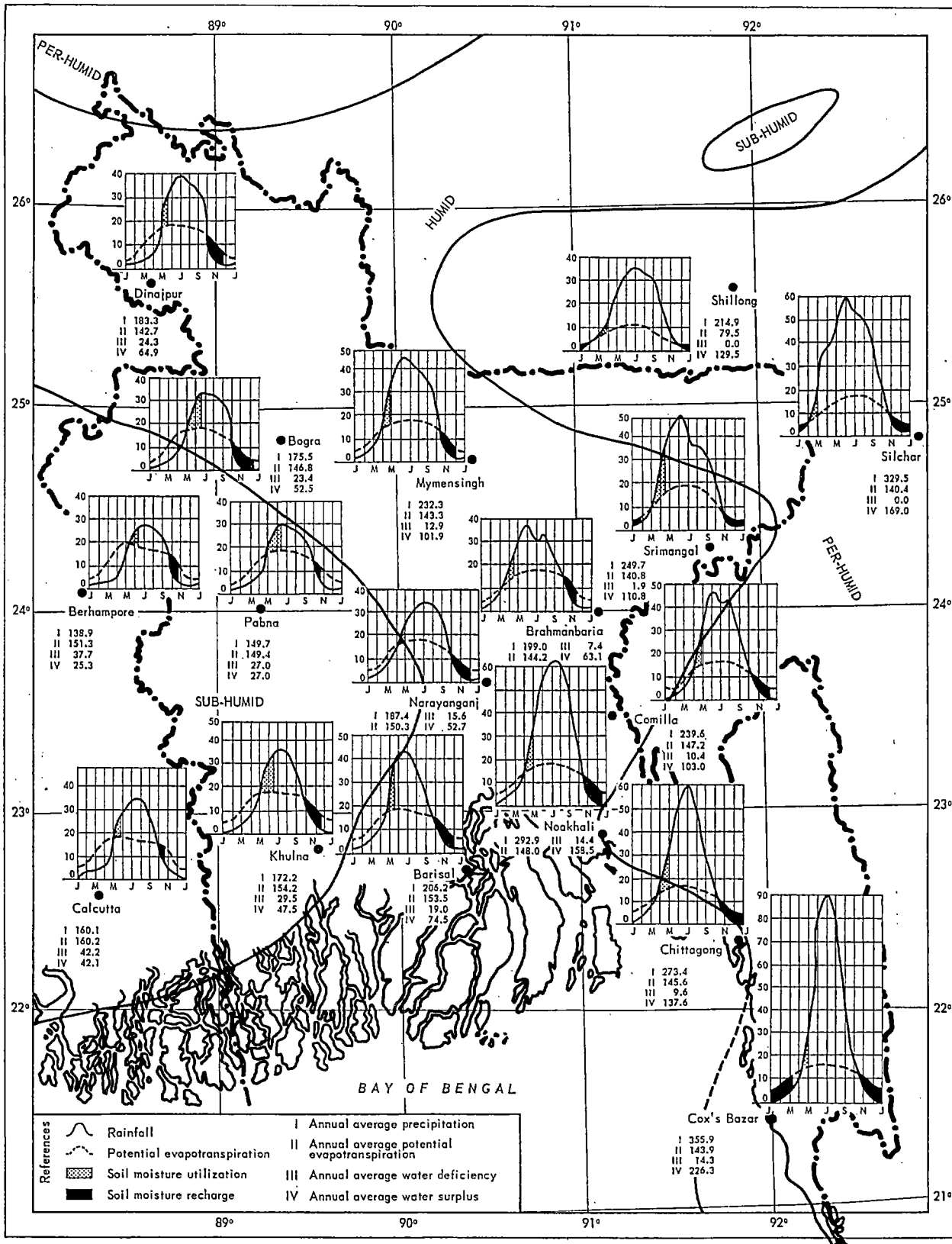

FIG. 6. Water balance in East Pakistan based on potential evapotranspiration and rainfall.

TABLE 2. Classification of climate according to Thornthwaite and Köppen

Station	Mean temperature		Average rainfall		Average annual				According to classification of		
									Thornthwaite		Köppen
	Coldest month (°F.)	Warmest month (°F.)	Wettest month (cm.)	Driest month (cm.)	Rainfall (cm.)	Potential evapotranspiration (cm.)	Water deficiency (cm.)	Water surplus (cm.)	Moisture index	Climate type	Climate type
Pabna	65.5	84.6	28.6	0.4	149.7	149.4	27.0	27.3	7.4	C_2 moist sub-humid	CaW humid subtropical mesothermal dry winter
Jessore	63.9	87.3	31.0	0.5	164.5						CaW humid subtropical mesothermal dry winter
Faridpur	64.2	83.4	32.5	0.4	180.1						CaW humid subtropical mesothermal dry winter
Narayanganj	66.7	83.7	33.7	0.5	187.4	150.3	15.6	52.7	28.8	B_1 humid	AaW tropical rainy savannah
Comilla	65.7	83.0	46.4	0.8	239.6	147.2	10.4	103.0	67.1	B_3 humid	AaW tropical rainy savannah
Khulna	66.9	84.9	36.7	0.5	172.2	154.2	29.5	47.5	19.3	B_2 moist sub-humid	AaW tropical rainy savannah
Satkhira	66.5	86.4	34.3	0.4	163.85						AaW tropical rainy savannah
Barisal	66.6	84.3	41.5	0.6	206.2	153.5	19.0	74.5	41.1	C_2 humid	AaW tropical rainy savannah
Noakhali	67.0	83.3	61.8	0.6	292.9	148.0	9.6	137.6	101.8	B_4 humid	AaWm tropical savannah rain forest

the rainy season when the discharge of the rivers is at its highest and the flow of the water into the sea is greatly affected.

The inundation due to the flood depends on the time of the arrival of the peak. If the flood peak arrives at the time of high tide the inundation is bound to be much larger than if it arrived at the time of low tide. This is particularly important because the slope of the flood-plains in this region is hardly 1 ft. in about 5 miles and the rivers carry tides throughout their courses in the delta.

CONCLUSIONS

The temperature conditions in East Pakistan with particular reference to the deltaic flood-plains have been examined in some detail and it has been found that maritime influence penetrates northwards up to Nasirabad and Rangpur districts and this appears to play a fundamental role in the origin of tornadic nor'wester squalls on the border areas to the east and west of this narrow belt and east of Jessore district where the continental air mass appears to persist. Their frequency is, therefore, much higher to the east and west of this belt.

Isothermal analysis appears to provide a key for the location of squally regions in this tropically humid area and it would be highly rewarding if more time were devoted to this type of analysis than has been so far in synoptic practice.

ACKNOWLEDGEMENT

During the preparation of this paper Mr. T. H. Siddiqui has greatly helped me by free discussion and useful suggestions at different stages, which I must acknowledge with thanks. I must also record that I have freely used for this study all the resources of meteorological data available in the Department.

TABLE 3. Suitability of different parts of East Pakistan for forest trees (from a climatic point of view)

Tree	Region suitable																Uses
	Barisal	Brahmanbaria	Bogra	Chittagong	Comilla	Cox's Bazar	Dinajpur	Faridpur	Jessore	Khulna	Mymensingh	Narayanganj	Noakhali	Pabna	Satkhira	Srimangal	
Adina cardifolia Hook	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	Wood for buildings; agricultural implements; furniture, cabinet making
Anthocepalus cadamba (Kaddam)	*	*	*	*	*		*	*	*	*	*	*	*	*	*	*	Corostock for veneer; matches; boxes; paper pulp
Bambax malabaricum (Semal) (Cotton tree)	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	Packing cases; matches; charcoal
Cassia fistula (Amaltas)			*				*	*	*	*				*	*	*	Houseposts; carts, carriages; agricultural implements; tanning products
Cedrela mexicana (Spanish cedar)	*	*	*	*	*		*	*	*	*	*	*	*	*	*	*	Furniture, cabinet making; boxes for tea and cigars; boat making
Cedrela toona (Red cedar toon)	*	*	*	*	*		*	*	*	*	*	*	*	*	*	*	Furniture, cabinet making; boxes for tea and cigars
Cinnamomum camphora (Camphor tree)												*					Furniture, cabinet making; camphor products
Dalbergia latifolia	*	*	*	*	*		*	*	*	*		*	*	*	*	*	Furniture, cabinet making; panelling; agricultural implements
Dalbergia sissoo (Sheesham)							*			*							Wood for buildings; fuel
Eucalyptus saligna (Sydney blue gum)					*												Wood for buildings; furniture, cabinet making
Eugenia jambolana (Jaman)	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	Wood for buildings
Gmelina arborea (Yemane)							*	*	*	*				*	*	*	Planking; panelling; furniture, cabinet making; matches
Hopea odorata (Thingun)				*		*											Wood for buildings; boat making
Hopea parviflora (Kango)			*			*	*	*	*					*	*	*	Wood for buildings; boat making
Pterocarpus macrocarpus (Padauk)			*				*	*	*	*				*	*	*	Carts, carriages; agricultural implements
Pterocarpus marsupium (Kino tree)	*	*	*				*	*	*	*		*		*	*		Wood for buildings; carts, carriages; ship building
Swietenia macrophylia (Honduras mahogany)				*										*			Furniture, cabinet making
Tectona grandis (Teak)			*				*										Wood for buildings; furniture, cabinet making; carts, carriages; shipbuilding
Terminalia arjuna			*				*										Wood for buildings; agricultural implements; boat making
Terminalia bellerica	*	*	*		*		*	*	*	*	*	*		*	*	*	Boxes; planking
Terminalia chebula	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	General construction
Terminalia myriacarpa											*		*				Wood for buildings; furniture, cabinet making; boat making

Résumé

Les problèmes météorologiques posés par les plaines d'inondation de la région du Delta au Pakistan-Oriental (Sibte Nabi Naqvi)

L'auteur examine d'une façon assez détaillée les conditions climatiques du Pakistan-Oriental et particulièrement des plaines d'inondation de la région du Delta. On a constaté que l'influence maritime s'exerce vers le nord jusqu'aux districts de Nasirabad et de Rangpur. Ce fait paraît jouer un rôle fondamental dans l'origine des tornades venant du nord-ouest sur les régions limitrophes situées à l'est et à l'ouest de cette étroite zone et à l'est du district de Jessore, où la masse d'air continentale semble persister. Ces tornades sont donc beaucoup plus fréquentes à l'est et à l'ouest de cette zone.

Le mémoire étudie aussi la question des cyclones tropicaux, celle du bilan hydrique et de l'utilisation des terres et des variations du niveau de la mer selon les saisons.

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Control of floods in East Pakistan

B. M. Abbas

East Pakistan, with an area of 55,100 sq. miles and an estimated population of about 55 million, is one of the world's most densely populated regions, the average density being 1,000 persons per sq. mile. In some parts the population density is as high as 3,000. The province, for the most part, consists of the flood-plains and delta of three big rivers, the Ganges, the Brahmaputra and the Meghna. These three rivers meet in the central part of the province and together carry a huge volume of flow to the Bay of Bengal through an expansive estuary. Due to the flat topography of the delta, the rivers overflow their banks during high flow periods and inundate large areas of the province. Floods are normal in East Pakistan and the people have learned through centuries to live with rivers and floods. Nature has assisted by providing types of rice, some of which can grow on dry land and others in flood-water, even to depths of 16 to 18 ft. But recurrent high floods are a threat to East Pakistan's economy. During the past nine years, the province has been subjected to four severe floods, inundating each time an area of about 15,000 sq. miles, or 10 million acres, which represents nearly half of the cultivable area of the province.

THE RIVERS

The Ganges and the Brahmaputra are two of the world's largest rivers; and the third large river, the Meghna, adds a considerable amount of flow into the main stream. These river systems drain a catchment area of about 626,000 sq. miles, of which only about 7.5 per cent lies in East Pakistan. A large part of the drainage area is in India, and a portion is in Tibet and Nepal.

The Ganges is 1,600 miles long, flows parallel to the Himalayan range and is fed mainly by rivers rising in the southern slopes of these mountains. Its total drainage area is 369,000 sq. miles, of which only 3.6 per cent, or 13,200 sq. miles, lies within East Pakistan. Gauge records since 1910 indicate a variation of less than 5 ft. between its highest and lowest annual maximum water levels. Discharge measurements started in 1934 show some degree of uniformity of maximum annual flows, which ranged from 1,350,000 to 2,160,000 cu. ft./sec. within this period. The highest stage was recorded in 1910 and the corresponding discharge is estimated at 3 million cu. ft./sec.

The Brahmaputra rises in Tibet and flows in an easterly direction north of the Himalayan range for a distance of 700 miles before turning south through the mountains, then it flows west down the Assam valley for a distance of 400 miles and enters East Pakistan as a wide braided river. The total length of the Brahmaputra to its confluence with the Ganges is 1,800 miles. Its watershed area is 225,000 sq. miles, of which 8.7 per cent, or 19,500 sq. miles, lies within East Pakistan. Gauge and discharge measurements of this river were started respectively in 1949 and 1956 at Bahadurabad, and the maximum recorded flood level occurred in 1958 with a corresponding discharge of 2,519,000 cu. ft./sec.

A flood discharge of the Ganges of 3 million cu. ft./sec. would be a reasonable expectancy, and a large flood flow in the Brahmaputra could be over 3 million cu. ft./sec.

The peak discharges of these two great rivers do not generally coincide but when high floods occur in both at the same time, as they did in 1962, it causes abnormally high flood levels below their confluence at Goalundo. Maximum observed discharges in 1962 were 2,407,000 cu. ft./sec. in the Brahmaputra and 2,160,000 cu. ft./sec. in the Ganges. Below Goalundo, where the combined flow is called the Padma, no measurement of discharge is taken.

The Meghna system is about 500 miles in length, of which about 260 miles lie in East Pakistan. Its drainage area is 29,500 sq. miles, of which 39 per cent, or 11,500 sq. miles, lies within East Pakistan. The maximum recorded flood stage at Bhairab Bazar occurred in 1955, and the corresponding discharge was 456,000 cu. ft./sec. It usually reaches its peak flood stage before

either the Ganges or the Brahmaputra, but is noted for its flashy tendency. The peak observed discharge in 1962 was 319,000 cu. ft./sec.

Below Chandpur, where the Padma joins the Meghna, the combined flow enters the Bay of Bengal as the Meghna. Tides of over 10 ft. occur in the Bay of Bengal. Tidal effect is observed in a decreasing degree up to Chandpur.

The Ganges flows for about 90 miles common to Pakistan and India before entering East Pakistan wholly on the eastern border a few miles above Hardinge Bridge, where the river has been stabilized at great cost. At the bridge the width is about 6,000 ft., but widens to over 10,000 ft. shortly after, and resumes a meandering pattern at within bank stages, cutting banks severely and building bars and shoals. The banks are not very high, appearing to be about 15 to 20 ft. at low stages and at maximum flood stages overbank depths average about 5 ft. The high water slope of the Ganges between Hardinge Bridge and Goalundo is about 0.30 ft. per mile. The river is moderately charged with suspended sediment at flood stages. There is, however, meagre data on suspended sediment and bed-load movement.

As the Brahmaputra enters East Pakistan in the north it is a braided river about 7 miles wide with *chars* (islands) of large size generally above normal flood stage. This width is not continuous as it flows 150 miles (approx.) to its junction with the Ganges, but the least width is about 4 miles. The available data indicate that the river carries a heavy sediment load. The high water slopes from the gauging station at Bahadurabad to the station at Goalundo (junction with Ganges) is about 0.35 ft. per mile. Below Goalundo, to the junction with the Meghna at Chandpur, the high water slope flattens to about 0.21 ft. per mile. With the great width of the river in this reach, overbank flooding was only 3 to 3.5 ft. at maximum observed stages.

THE PROBLEM

As floods caused by high run-off and tidal inundation are a grave threat to the security and economy of the people of East Pakistan, protective measures must be quickly afforded to flood-ravaged areas if only to preserve the existing economic status of the province, where millions subsist on meagre diets and low incomes. Floods in East Pakistan annually cause widespread damage to properties, standing crops and farm animals, followed by epidemics caused by hunger, exposure and unsanitary conditions in the flood-affected regions. The rapidly expanding population in the already densely populated areas adds urgency to the problem.

SOLUTIONS

General

The flood problem in East Pakistan is complex and unique. The province is situated in the delta region of the big rivers and because of its flat topography, it is difficult to visualize an enduring and effective control of floods within East Pakistan in the near future. Nevertheless, the flood conditions can be greatly alleviated by remedial measures that are applicable to East Pakistan. These works require a thorough study and should be provided in a rational and phased programme.

The vast quantities of flood-waters that are carried by the rivers through East Pakistan and which spread over much of the land are the result of run-off from precipitation falling, for the greater part, outside of the province. As mentioned previously, only 7.5 per cent of the drainage areas lie inside East Pakistan. Considering the enormous costs to be expended in controlling these floods and the economic condition of Pakistan, it is obvious that the major responsibility for remedial measures should be taken up by international agencies.

Reservoir impoundment

In East Pakistan the impoundment and regulation of flood-water is impractical due to the relatively flat terrain of the deltaic region. There are no suitable reservoir sites on these rivers wherein substantial quantities of their flood flows could be impounded with a view to regulating the discharge. Such storage sites would be available in the upper reaches of these rivers which lie in India, Tibet and Nepal. These rivers could be harnessed and their floods controlled if there were co-operation from these countries in undertaking a basin-wide study and putting up a joint effort in implementing flood control works. After the two severe floods in the consecutive years of 1954 and 1955 in the eastern region of the Indo-Pakistan subcontinent, the governments of Pakistan and India agreed to explore the possibilities of finding ways and means to tackle the flood menace which had been causing untold miseries to millions of people in both countries. However, the discussions so far held have not proceeded beyond exchange of some information between the two countries.

Embankment

Embankments placed on both sides of the river to confine all or to a large extent the flow within the banks is the method which would continue to be the main measure of flood protection. Total exclusion of flood-waters from an agricultural area is not, however, always desirable. It involves changing the existing cropping patterns and life-long habits of the people. With the exclusion of flood spills, new practices have to be introduced to work the land. In the initial stage of flood control, the problem of flooding along the major rivers may be tackled in the sense of overflow regulation. If the river flow is confined to a suitable degree by means of embankments, it is expected to be helpful in developing a more efficient channel.

Channel improvements

This method of flood control is suitable for the delta area in East Pakistan where there is a network of channels having many degrees of water-carrying capacities. These have to be widely used in effectively giving more direct outlets of flood-waters to the sea. The channels include the existing main channels and also the secondary spill channels which may be partly silted up. Such improvement provides increased channel-carrying capacity by use of river training works to prevent erosion, shortening, widening and deepening of the river channel. Barrages and regulators may be provided where feasible to divert and control the flow into the secondary by-pass channels.

Drainage projects

Such projects will be an essential feature in a programme of flood control in East Pakistan and will consist of both pump drainage and gravity draining of monsoon run-off which accumulates in depressions. Gravity drains should be provided where they are effective independently or in conjunction with pump drainage projects. Drainage projects will expedite run-off and thereby reduce or even prevent overflow of rivers.

Flood warning systems

Flood protection should include long-range predictions of high seasonal discharge, based on snow surveys and short-range warnings based on intensity of rainfall and river stage levels. Since most of the catchment area is outside East Pakistan, co-operation of other countries within the basins is necessary for transmitting the information in time to East Pakistan.

PROGRAMME

In 1956, the Government of Pakistan obtained the services of a United Nations technical mission to make an on-the-spot study of the flood problems of East Pakistan. The mission noted in its report that basic data was inadequate; that an authority should be established for the comprehensive development of water and power resources of the province; and that joint action by India and Pakistan would produce best results in the development of international rivers.

In 1959, the East Pakistan Water and Power Development Authority (EPWAPDA) was created for the unified and co-ordinated development of water and power resources of the province. At that time there were inadequate contour maps and meagre hydrological

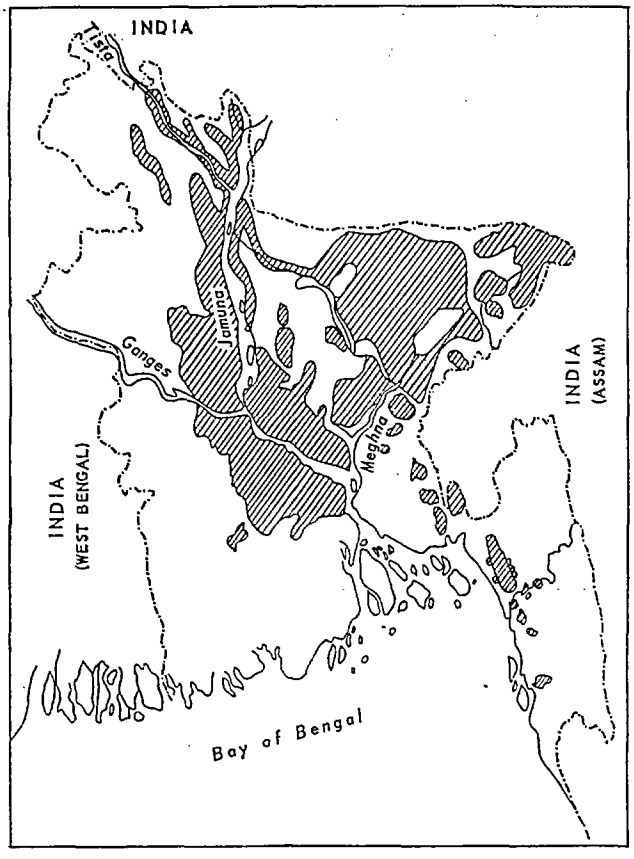


FIG. 1. Upland flooded areas of East Pakistan in 1962.

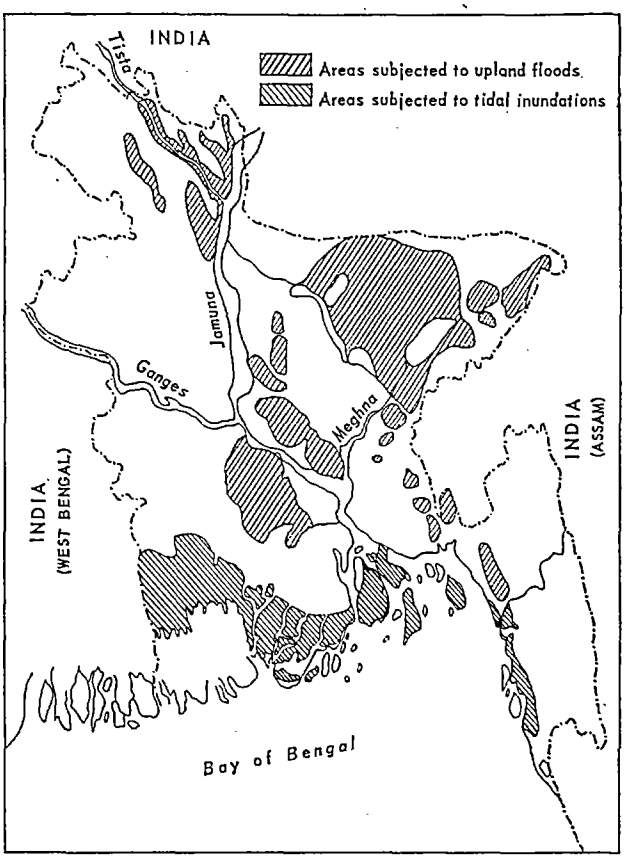


FIG. 2. Normal flooded areas in East Pakistan.

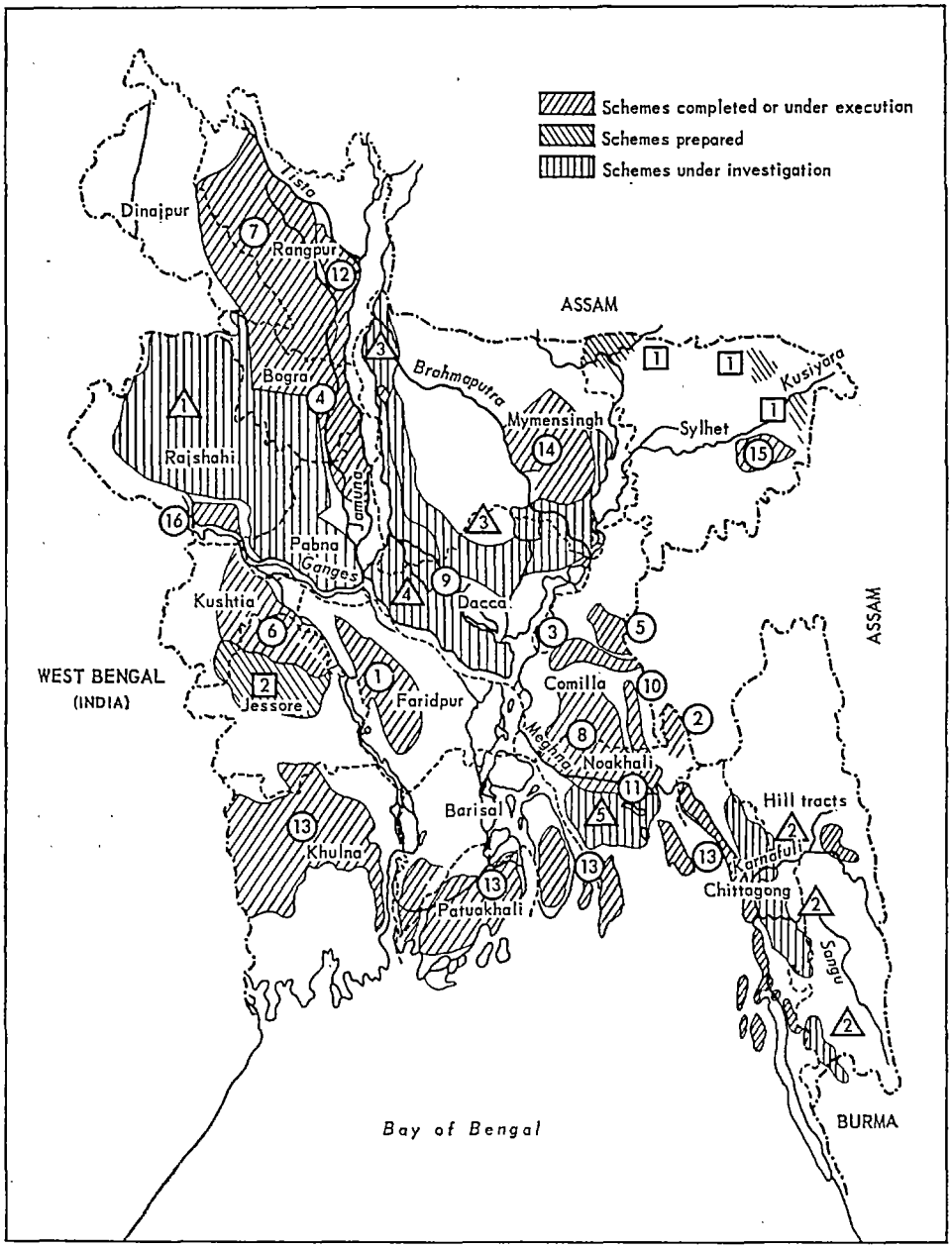


FIG. 3. East Pakistan Water and Power Development Authority projects proposed to date for protection of flood-affected areas. See key to figures on page 139.

data. The EPWAPDA has proceeded vigorously with the collection and compilation of basic data necessary to develop plans for the control of floods. Preparation and implementation of flood protection projects has progressed despite lack of foreign exchange and technical data and shortage of technical personnel.

Figure 1 shows a total area of nearly 10 million acres submerged by the upland flooding of 1962, of which about 5.9 million acres of land were severely damaged. This figure excludes the lands which are normally inundated every year by upland flooding and tidal action as shown in Figure 2. The EPWAPDA schemes so far conceived to provide protection against both upland floods and tidal inundations are shown in Figure 3. For the area subjected to damage from rainfall and river overflow, the EPWAPDA has already conceived projects which will ultimately provide for the protection of about 4 million acres. Construction of works are in progress or will shortly start to provide protection to an area of about 1.9 million acres. Schemes have been prepared for the protection of another 560,000 acres. Investigations are already in progress or

SCHEMES UNDER EXECUTION:

1. Comprehensive drainage scheme in Faridpur district
2. Prevention of floods in Feni sub-division of Noakhali district
3. Dredging the River Gumti in the district of Comilla and strengthening the Gumti left and right embankments
4. *Improvement of the Gazaria-Ichamati river in Bogra district*
5. Re-excavation of Ghungur, Salda and Buri Nadi in the district of Comilla
6. Ganges-Kobadak project, Kushtia unit
7. Tista barrage
8. Tippora-Chittagong multi-purpose project (phase I)
9. Dacca-Narayanganj-Demra project
10. Improvement of old Dakatia and Little Feni river in the district of Comilla, and Noakhali
11. Comprehensive drainage scheme for Sadar sub-division of Noakhali district
12. Brahmaputra flood embankment, Kaunia to Serajgang
13. Coastal embankment project
14. Old Brahmaputra project (phase I)
15. Manu river project
16. Southern Rajshahi irrigation project

SCHEMES PREPARED

1. Haor Reclamation: Bara Haor, Hakaluki Haor and Jadukata flood control
2. Ganges-Kobadak project Jessore unit (phase I)
3. Development of the Gumti

SCHEMES UNDER INVESTIGATION

1. Investigation of comprehensive drainage flood protection and irrigation scheme in Rajshahi, Pabna and Bogra district
2. Development of the Sangu, Mathamuhari and Halda rivers
3. Brahmaputra left bank flood embankment
4. Dacca south-west Irrigation project
5. Noakhali reclamation project

will soon be under way for protection of about 1.5 million acres of flood-damaged lands.

The coastal embankment project now under construction will reclaim a total of 3.4 million acres of arable land from inundation by saline sea water during high tides. Of the total 3,000 miles of embankment proposed for the project, about 1,050 miles have been completed, protecting an area of about 1 million acres.

Other major embankment schemes include the completed Gumti embankments and the 135-mile flood embankment on the right bank of the Brahmaputra-Jamura river from Kaunia to Sirajganj being just started. The multi-purpose projects which will afford protection include the completed Karnafuli hydro-electric project and the continuing Ganges-Kobadak, Tista barrage and Dacca-Narayanganj-Demra projects as well as new schemes being taken up such as the Old Brahmaputra project (phase I), Chandpur irrigation project (Tippera Chittagong, phase I), the Manu river project and the southern Rajshahi project.

Flood-drainage benefits will be provided by the completed Gumti dredging scheme and the Ghungur Salda-Buri Nadi scheme in the Comilla district; the comprehensive drainage scheme in Faridpur district nearing completion; and the Old Dakatia-Little Feni scheme, Feni flood-protection scheme and Noakhali Sadar sub-division scheme now under construction. Soon to be under investigation are the Hail Haor and Noakhali reclamation projects. There are also large numbers of completed and continuing small schemes of the embankment and drainage types designed to benefit local areas in different parts of the province. A project has been initiated for the construction of a barrage across the Ganges below Hardinge Bridge which will have the multi-purpose object of irrigation, drainage and flood regulation for the south-west zone of the province. Continuing investigations include the investigation of comprehensive drainage, flood protection and irrigation scheme in Rajshahi, Pabna and Bogra districts, and the development of the Sangu, Mathamuhari and Halda rivers. Work is also in progress on the collection of basic data regarding the Brahmaputra, which will enable consideration of the feasibility of any scheme of regulation of flood of this river. Projects to be developed from the Brahmaputra investigations include the Old Brahmaputra project (phases II and III), the Brahmaputra left bank flood embankment and the Dacca south-west irrigation project.

A master plan for the over-all development of water and power resources of East Pakistan is now under preparation. Planning for flood control is one of the principal items of this study.

Résumé

Lutte contre les inondations au Pakistan-Oriental
(B. M. Abbas)

Avec ses 55 millions d'habitants répartis sur une superficie de 143 000 km², le Pakistan-Oriental est l'une des régions les plus peuplées du monde (densité moyenne : près de 400 habitants au km²). La province est constituée en majeure partie par les plaines inondables et le delta de trois grands fleuves : le Gange, le Brahmapoutre et la Meghna.

Les inondations y sont un phénomène normal, et la population a appris au cours des siècles à s'en accommoder; mais depuis neuf ans, la province a connu quatre inondations importantes qui ont recouvert chaque fois près de 40 000 km², soit près de la moitié de la superficie des terres cultivables.

Le réseau hydrographique

Le Gange et le Brahmapoutre, deux des plus grands fleuves du monde, se combinent avec le troisième fleuve important, la Meghna, pour drainer un bassin de plus de 1 million de kilomètres carrés, dont 7,5 % seulement font partie du Pakistan-Oriental. Le reste appartient au Tibet, au Népal et surtout à l'Inde.

Le Gange a 2 700 kilomètres de long, et la crue la plus forte que l'on ait enregistrée dans son lit est celle de 1910, où son débit fut évalué à 85 000 m³ par seconde. Le Brahmapoutre a 2 900 kilomètres de long, et on estime que son débit en période de crue pourrait dépasser 85 000 m³ par seconde. Quant à la Meghna, longue d'environ 800 kilomètres, sa crue la plus forte, depuis que l'on procède à des enregistrements, a été celle de 1955, où son débit était de 13 000 m³ par seconde.

Le problème

Les crues causent chaque année, dans les régions fortement peuplées du Pakistan-Oriental, d'importants dégâts aux habitations et autres bâtiments; les récoltes sur pied et le cheptel en souffrent également; en outre, la famine qui en résulte, la pénurie de logements et l'insalubrité des régions inondées sont génératrices d'épidémies.

Solutions

Étant donné que les énormes quantités d'eau que les fleuves en crue charrient à travers le Pakistan-Oriental, et qui viennent inonder une grande partie des plaines deltaïques, proviennent de précipitations captées par un bassin versant situé, dans la proportion de 92,5 % de sa superficie totale, en dehors du Pakistan-Oriental, c'est évidemment à des organisations internationales qu'il incombe au premier chef de prendre des mesures contre les inondations. Cependant, les autorités du Pakistan-Oriental comptent appliquer par étapes successives un programme rationnel dont voici les principaux éléments :

Aménagement de réservoirs. Étant donné l'absence relative de relief dans la région deltaïque, il n'y a, le long des principaux fleuves, aucun site où l'on puisse retenir une partie des eaux de crue pour en régulariser l'écoulement : de tels sites existent cependant sur le cours supérieur de ces fleuves, en Inde, au Tibet et au Népal. Des pourparlers entre le gouvernement pakistanais et le gouvernement indien, sur la façon de résoudre le problème commun que constituent les risques d'inondation, ont uniquement abouti jusqu'à présent à l'échange de quelques renseignements entre les deux pays.

Endiguement des fleuves. La principale mesure de protection contre les inondations consistera à endiguer les fleuves de manière à retenir entre leurs berges la totalité ou la majeure partie des eaux de crue.

Amélioration des chenaux. On augmentera la capacité de débit du réseau des chenaux par la construction de digues latérales combinées, lorsque cela sera possible, avec des barrages et prises d'eau destinés à régulariser l'écoulement et diriger les eaux vers des chenaux secondaires de dérivation.

Travaux de drainage. Des travaux de drainage (pompage ou drainage par gravité des terres basses) accéléreront l'écoulement et permettront de réduire, sinon d'empêcher, les inondations.

Systèmes d'alerte aux crues. Des mesures de l'enneigement permettront de faire des prévisions à long terme sur le niveau des hautes eaux saisonnières; d'autre part, les renseignements concernant l'importance des précipitations et le niveau des eaux en divers points des fleuves, reçus des pays où ces fleuves ont la majeure partie de leurs bassins versants, permettront d'établir un système d'alerte à court terme.

Programme

En 1956, une mission d'assistance technique des Nations Unies, chargée d'étudier sur place les problèmes que posent les inondations au Pakistan-Oriental, a signalé l'insuffisance des données de base disponibles; elle a recommandé la création d'un organisme spécial pour l'exploitation rationnelle de l'ensemble des ressources hydrauliques et souligné qu'une action commune de l'Inde et du Pakistan serait particulièrement favorable à la mise en valeur des fleuves communs au Pakistan et aux pays voisins.

En 1959, la Water and Power Development Authority du Pakistan-Oriental a amorcé la création d'un système unifié et coordonné d'exploitation des ressources hydrauliques en s'attachant vigoureusement à réunir des données fondamentales et à en faire la synthèse, ainsi qu'à préparer et à exécuter des travaux de protection contre les inondations.

Les projets actuels, une fois réalisés, permettront de protéger une superficie d'environ 1,6 million d'hectares, dans les régions sujettes aux inondations provoquées soit par les précipitations, soit par le débordement des fleuves. Les ouvrages en construction ou dont la construction commencera d'ici peu assureront la protection d'environ 760 000 hectares; des plans ont été dressés pour la protection de 225 000 hectares; en outre, des recherches sont en cours ou seront prochainement entreprises pour assurer la protection de 600 000 hectares supplémentaires. Le long du golfe du Bengale, on construit aussi une digue côtière qui permettra de protéger 1 360 000 hectares de terres que la mer recouvre à marée haute. Cette digue existe déjà sur 1 700 kilomètres et assure dès maintenant la protection d'environ 400 000 hectares.

Un plan d'ensemble pour l'exploitation générale des ressources hydrauliques du Pakistan-Oriental est actuellement en préparation.

Surface hydrology of deltaic areas

A. Volker

INTRODUCTION

Hydrology is usually defined as the interdisciplinary science of the occurrence and movement of water upon and beneath the land areas of the globe. For practical reasons surface hydrology is treated as an individual subject but there exists a most intimate relation with the conditions of the ground water. This is especially so in deltaic areas where the ground-water table occurs at a shallow depth below the surface.

Surface hydrology of deltaic areas presents some features which distinguish themselves from surface hydrology of the upper portions of the river basin. This is due to the following specific conditions: (a) the small slopes of the river and the land areas; (b) the effect of the tidal levels on the river stages and the intrusion of saline water from the sea; (c) the network of river branches and ramifications; (d) the rapid changes in the channel configuration that may take place; (e) the low elevation of the land areas.

The basic hydrologic processes are virtually the same in all the deltaic areas of the various climatic zones. In the deltaic areas of the humid tropical zone hydrologic conditions are characterized by the high precipitation and evaporation rates according to the monsoon, the type of river flood and by the fact that most of the deltas in the humid tropical zone are still in a preliminary stage of technical development.

This paper deals with both the hydrology of the river and its branches and the surface hydrology of the land areas in a delta. This relation is most pronounced in deltas where water control is not yet adequate. At high river stages and high sea levels the land is liable to be flooded; the drainage conditions of the land areas depend on the river stages; the extent of the salt-water intrusion in the rivers influences the salinity conditions of the land areas; etc. The deltaic areas of the Ganges (India and East Pakistan), Irrawaddy (Burma), Chao-Phya (Thailand), Mekong (Viet-Nam), Pampanga (Luzon, Philippines) to which reference is made, offer many examples of the interdependence of hydrologic conditions of the river and the land areas. This has an important bearing on the agricultural land use.

The relation is less pronounced in those deltaic areas where technical measures of flood protection and water control have been taken. Typical examples are found in the deltas of rivers in Japan which are also briefly discussed.

Human interference in the hydrologic conditions of a certain part of a deltaic area may have repercussions on the conditions in other parts. This is another typical feature of the surface hydrology of deltaic areas.

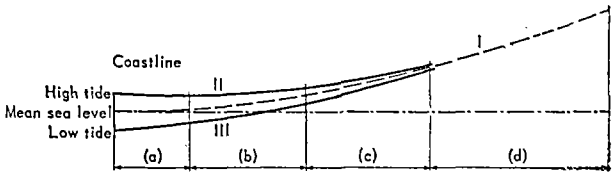
HYDROLOGY OF THE RIVER AND ITS DISTRIBUTARIES

The hydrologic conditions of the river in the deltaic reach are governed by the type of floods, the flow in dry periods, the intrusion of saline water from the sea and the sediment transport. These features differ widely in the various deltaic areas in the humid tropical zone. They provide a partial explanation of the differences in land utilization and hydraulic development that have taken place.

Type of floods

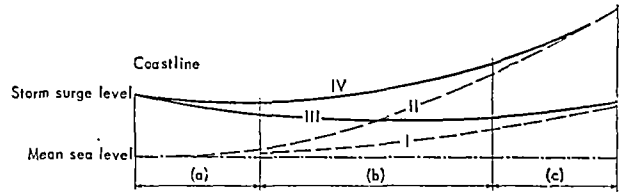
Deltaic areas are exposed to the floods caused by the propagation of tidal levels along the coasts and to the floods coming from the upstream portions of the river basin.

According to the propagation of the astronomical tides the river can be divided into the following reaches (Fig. 1): (a) where vertical tides occur with subsequent reversal of the current direction and intrusion of saline water; (b) where the river water is fresh but otherwise the tidal phenomena are similar to those in the previous reach; (c) where the water levels are still affected by the tides but where the current direction remains the same but with varying velocity according



I = at average discharge and mean sea level
II = at high tide on the sea
III = at low tide on the sea

FIG. 1. Subdivision of the tidal reach of a river according to the tidal phenomena.



I = at low discharge and mean sea level
II = at flood discharge and mean sea level
III = at low discharge and storm surge level
IV = at flood discharge and storm surge level

FIG. 2. Subdivisions of the deltaic reach of a river according to the type of predominant flood.

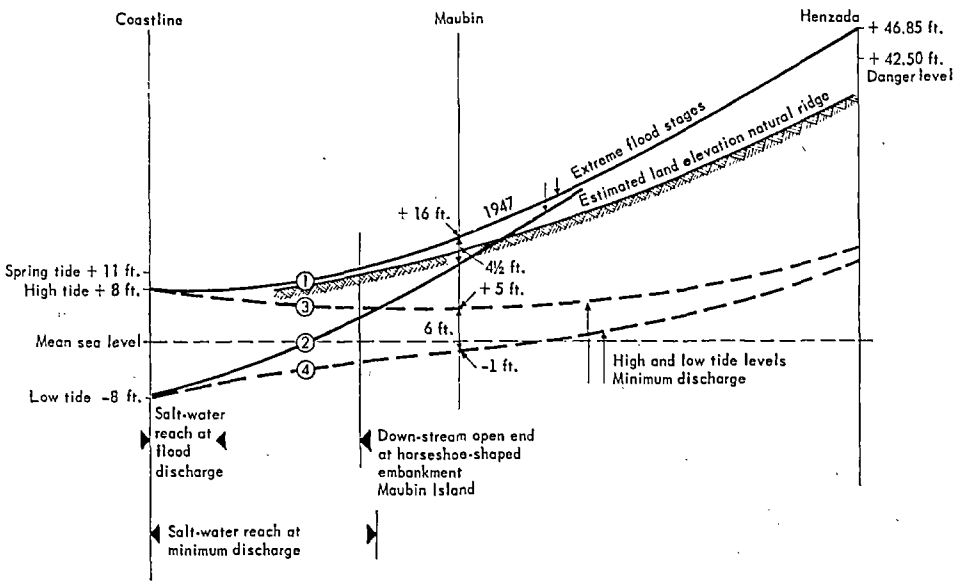


FIG. 3. Longitudinal profile of the flood and tidal stages of the Irrawaddy (Burma).

to the tide; (d) where the water levels and the flow are only affected by the upstream discharge.

According to the propagation of abnormally high sea levels as caused by storm surges, the river can be divided into the following reaches (Fig. 2): (a) where the effect of the sea levels predominates; (b) where a combined effect of sea and river floods occurs (intermediate zone); (c) where the effect of the river floods predominates.

As explained in the later paper on the tides, storms and coastal currents, the magnitude of the rise of the sea level due to storm surges varies widely from one area to the other. Rises of some metres may occur along the deltaic area of the Ganges and the deltas in Japna and China (Taiwan); they are practically non-existent along the coasts of the Irrawaddy (Burma), Chao-Phya (Thailand), Mekong (Viet-Nam) and Pampanga (Luzon, Philippines).

Figure 3 gives a longitudinal profile of the flood and tidal stages along the Irrawaddy. The profile starts at Henzada near the apex at a distance as the crow flies of 210 km. from the sea. The extreme flood stages are determined by the upstream floods and the astronomical high tide. The absence of abnormally high sea levels has made possible a peculiar form of land utilization in the tidal zone of the delta as is explained in greater detail in the description of the Irrawaddy delta (see the article by the same author in Part VI).

The river floods are generated in the upper catchment and in the deltaic area. Thus the climatologic and physiographic conditions of the upstream river basin and the ratio between the sizes of the upper catchment area and the deltaic area are of primary importance.

The characteristics of the river basin determine the type of upstream flood with respect to the duration of the flood and the rate of rise and fall of the flood peaks. Typical differences are illustrated in Figure 4 giving annual hydrographs of the Chao-Phya (catchment area 160,080 sq.km.) and the Cho-Shui (China (Taiwan), catchment area 3,150 sq. km). These differences are mainly due to the difference in areal extent of the river basins. Thus for the small and short river basins the floods are flashy, whereas for the large basins

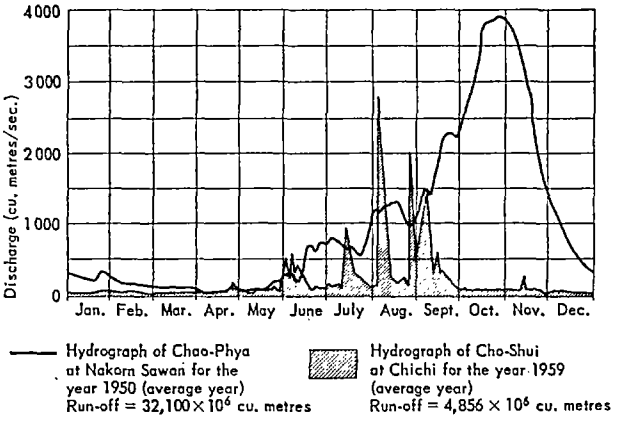


FIG. 4. Average annual hydrographs of the Cho-Shui (China (Taiwan)) and Chao-Phya (Thailand).

the effect of rainfall on the outflow from the basin is distributed over a longer period.

Flashy floods also occur in the rivers in Japan and in the Red River in northern Viet-Nam (catchment area 120,000 sq. km.), where the variability of the heavy rainfall, the steep slopes and low infiltration capacities of its river basin are responsible for the nature of the floods.

Flood protection

The type of flood hydrograph determines whether, in the first stage of land utilization, flood protection by embankments is an absolute necessity or not. Where the floods are flashy no utilization of the deltaic areas at all would be possible without high embankments. If on the other hand the river level rises gently and the flood volume is spread over several mouths, paddy can be grown over large areas with modest means of flood control. This is the case in the deltaic areas of the Irrawaddy, the Chao-Phya and the Mekong.

The ratio between the size of the river basin upstream of the deltaic area and the size of this area determines to what extent the effect of the floods can be attenuated by the construction of flood control revervoirs in the upper portion of the river basin. For the River Kiso in Japan this ratio is about 7 (river basin 5,000 sq. km., delta 720 sq. km.); for the River Pampanga in Luzon it is about 3 (river basin including tributaries 6,900 sq. km., delta and flood plain 2,210 sq. km.).

In the Kiso river basin many dams have been built reducing substantially the peak flows, whereas in the Pampanga plain storage reservoirs would have little effect on the flood conditions in the delta.

The natural depressions or back swamps in deltaic areas have a considerable effect on the propagation of the floods from upstream. The depressions act as natural detention reservoirs where a substantial portion of the flood volume is retained in temporary storage

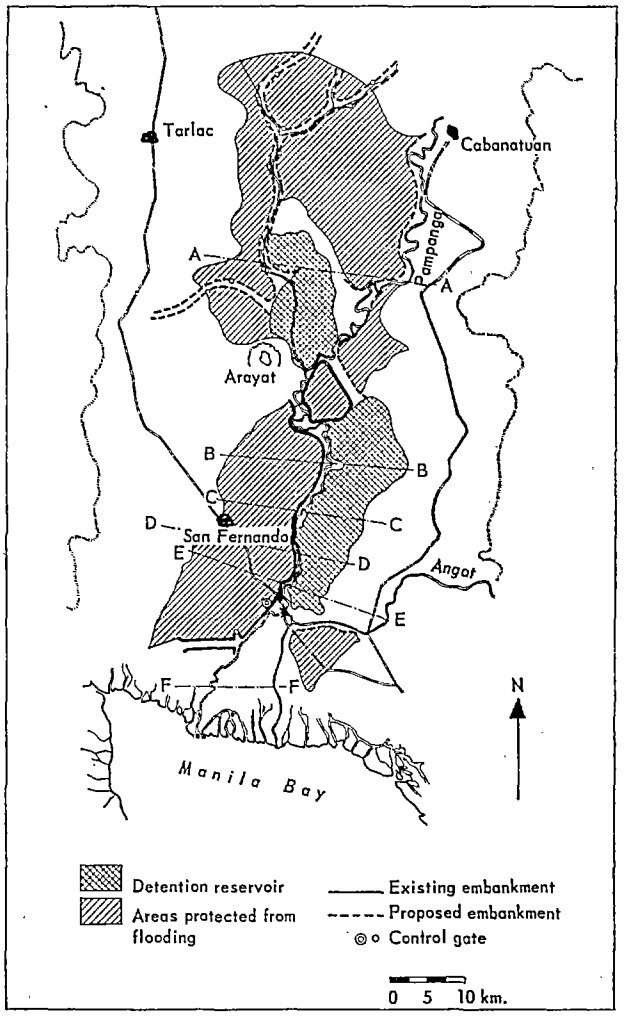


FIG. 5. Natural detention reservoirs and flood control system in the Pampanga (Luzon, Philippines).

thus reducing the highest flood stages. This effect is more pronounced for flashy floods than for floods of a long duration.

Figure 5 gives the flood control system in the lower reach of the Pampanga river. The floods in this area are flashy (the river stage may rise as much as 2 metres in 24 hours) and a considerable portion of the plain has been protected by embankments. Projects are being studied or are under execution to further reduce flood damages by an extension of the dike system. The Candaba and San Antonio swamps (Fig. 6) will, however, continue to act as detention reservoirs. Embanking of these areas would cause the maximum flood stages to rise several metres.

Minimum flow and salt-water intrusion

The physical characteristics of the river basin also determine the flow during rainless periods. This flow

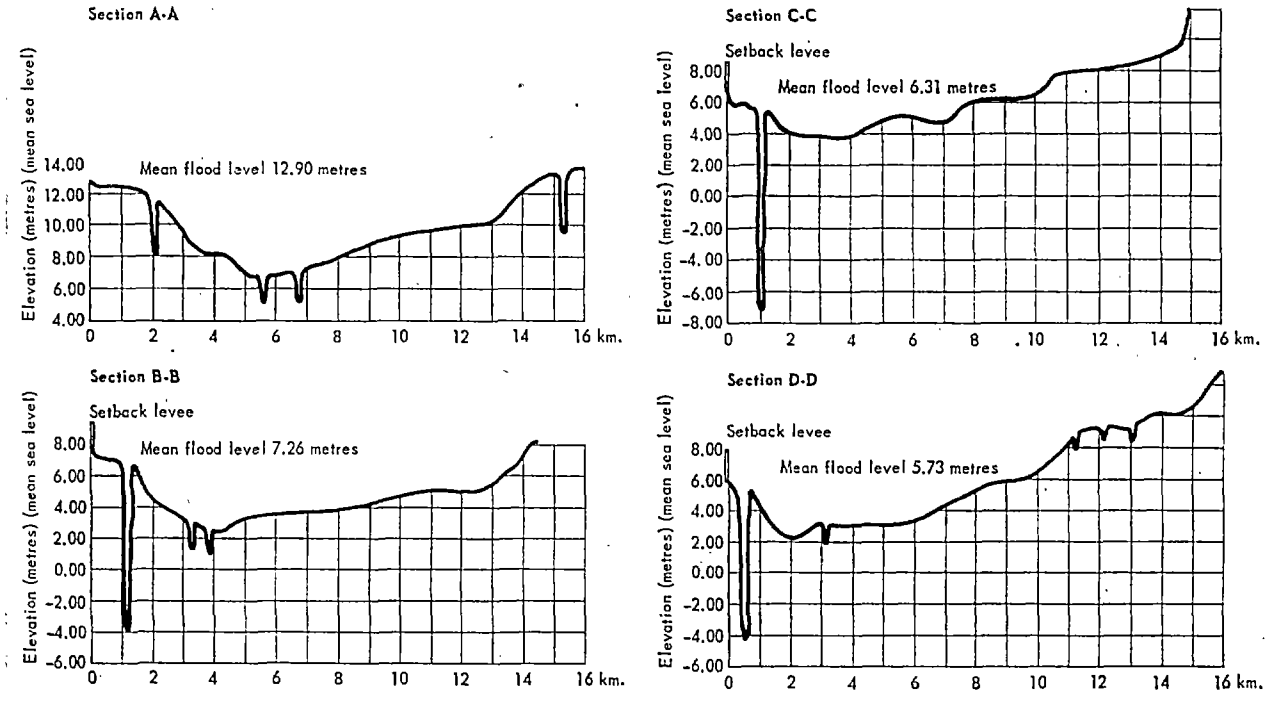


FIG. 6. Cross-sections of the natural detention reservoirs in the Pampanga river system. Horizontal scale: 1 : 100,000; vertical scale 1 : 200. Mean flood level as in August 1960.

is important with respect to the intrusion of sea-water, the availability of irrigation water and the hydraulic conditions of the river.

Because of its higher density the sea-water intrudes in the river mouths mixing with the freshwater flow by turbulence and by the tides. At any point along the lower course of the river the highest salt content is found near the bottom. The salinities in a given location vary with the tidal phase.

The distance from the coastline over which salt-water intrusion takes place depends on the tidal ranges and on the freshwater flow from the river. At Ayuthaya, on the Chao-Phya 136 km. from the sea, the salt content of the river-water near the bed may be as high as 2,000 p.p.m. of total salts per litre at a minimum discharge of some 60 cu. metres per sec., whereas during floods (4,000-5,000 cu. metres per sec.) the river-water is fresh not only at Ayuthaya but even at only a few kilometres from the sea.

In many deltaic areas of the humid tropical zone the salt-water intrusion during the floods is hardly of any importance but the situation is different during the dry period.

In the Sunderbans area in India and in the western part of the Sunderbans in East Pakistan the saline water is encroaching still further due to subsidence and the decrease of the freshwater supply from upstream.

Sediment transport

The problems of sediment transport in the deltaic reach of a river are of great practical importance. The deltaic reach is virtually an area of deposition of sediments and rapid changes in the configuration of the channel system. Any human interference in the natural processes of scouring and deposition is likely to create repercussions.

From an engineering point of view, distinction can be made between the "active zone" where important changes take place and the "non-active zone" where a certain equilibrium has been reached and where conditions of beds and alignments of channels are relatively stable. In the active zone the execution of engineering works may encounter paramount difficulties. In the non-active zone engineering works can be planned in such a way as to gradually change the natural situation without abrupt upset of the equilibrium.

Major problems are the effect of embanking on the position of the river bed both in the tidal and upstream portions of the river and the effect of cut-off and diversion works on the river régime. These problems will be dealt with in another paper but their bearing on the hydrologic conditions is obvious.

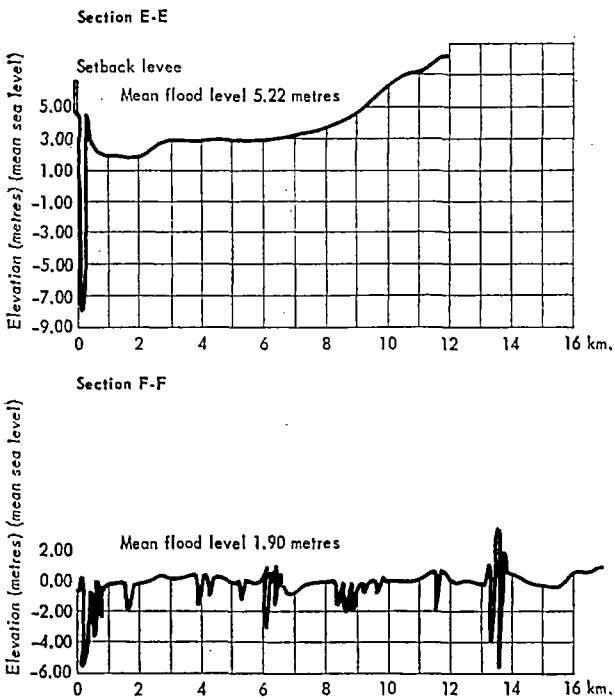


FIG. 6. (*continued*)

Hydrologic measurements

There exists a general lack of data on the hydrologic conditions of the deltaic areas in the humid tropical zone. It is anticipated that the programme for the Hydrological Decade as planned by Unesco will fill up a part of the gaps.

When hydrologic data is missing priority should be given to the collection of continuous records on the river stages and discharges at the apex of the delta. By intermittent measurements the relationship between the river discharge (both for rising and falling river stages) and the transport of solid material (bed-load and suspended load) can be established.

When extending the collection of these data to other points along distributaries in the non-tidal zone use can be made of relationships between stages and discharges which can be established after short measuring periods.

In the case of floods with considerable overbank storage records of the water levels in the flooded areas in several locations are needed.

The data to be collected in the tidal zone should be related to the tidal levels at the coastline. For this recording tidal gauges distributed over the entire length of the coastline of the delta are required.

In the estuaries and lower reaches of the river branches in the tidal zone data is required on the water levels, salinities and silt content. The nuer of themb recording tidal gauges can be limited if the data collected in these fixed stations can be supplemented by measurements of tidal levels and tidal currents over a short period at temporary intermediate stations. Correlation of simultaneous measurements at the various stations with the long-term observations at the fixed station will give a general conception of the tidal conditions in the delta.

HYDROLOGY OF THE LAND AREAS

The surface hydrology of the land areas in deltas is governed by the climatic conditions and the physical characteristics of the areas as well as by the régime of the river. This is caused by the low elevation of the land which is liable to flooding. Another typical feature is the topography of the land which is basin-shaped by the presence of natural levees and back swamps.

The hydrologic conditions in the land areas of the humid tropical zone are characterized by a close relationship between micro-topography, flooding and land use.

In deltaic areas without major flood protection works the hydrologic conditions of the land areas differ according to the river reach:

1. The zone principally affected by the river flood. In the flood season this zone may be flooded for several months (Chao-Phya, Mekong). After overtopping of the banks the depressions are filled and the water starts to move slowly in a seaward direction. Drainage only takes place at the recession of the floods and in some depressions the water may remain stagnant for most of the year. In the deltaic areas of the Irrawaddy, Chao-Phya, Mekong and Pampanga a variety of rice known as "floating rice" is raised which can grow in a water depth of 3 to 4 metres and attain a stem length of 4 to 5 metres provided that the daily rise of the water level does not exceed 5 to 10 cm.
2. The zone where tidal flooding is predominant. In this zone the land is flooded with saline water during the highest spring tides and on the occurrence of storm surges. There are, however, good drainage possibilities because of the low-water tides.
3. The intermediate zone. In the flood season the water in this zone is fresh due to the high river flood. The effect of the upstream flood discharge on the river stages in this zone is comparatively small so that the depth of flooding is moderate and no damage by saline water occurs. Moreover, at low tide the water is drained off, at least to a certain extent.

In deltaic areas where a certain degree of flood protection has been achieved (Irrawaddy, Chao-Phya, Pampanga, Sunderbans in the coastal zone), the hydrologic conditions of the land areas can be controlled:

1. The zone where the effect of the river floods is predominant. Embankments (or river levees) in this zone can eliminate the high-river stages. In the case of floods of long duration the drainage of local water excess still poses a problem and adequate drainage can only be achieved by pumping. There are no areas of any considerable size in the humid tropical deltas where artificial drainage by pumping has been applied, the present land use and yields being insufficient to justify the costs. There are, however, several examples of drainage by pumping in the deltaic areas in Japan.

   Irrigation in this zone, either as supplementary irrigation or as dry season irrigation, can be effected by direct intake from the river or through a headwork.

   In the deltaic area of the Irrawaddy flooding of the land areas is prevented by a system of embankments. In the neighbouring delta of the Chao-Phya, the flood-waters are deliberately admitted to the fields by a system of headworks, regulators and canals. The explanation of this difference lies primarily in the average amount of rainfall during the growing season: about 1,000 mm. in Thailand against some 2,000 mm. in Burma, whereas the water duty of the rice crop can be estimated to be about 1,500 mm.
2. The zone where the water levels are determined by the tides. In many deltaic areas in the tropical humid zone coastal embankments or sea-dikes have been erected to prevent flooding with saline water. The low tides can be used for draining excess water from rainfall. The penetration of high tides and the outflow of water when no drainage is desirable, can be prevented by movable gates in the sluices at the outfalls to the sea.

   The drainage of interior areas at considerable distances from the outfalls may pose a problem since the effect of the tidal gravity drainage is limited to a certain distance.
3. The intermediate zone. The tidal ranges in this zone are smaller than in the coastal zone which may prohibit gravity drainage and lead to pumping. As far as the river water in this zone is fresh, irrigation water can be admitted at high tide.

Areas in which the water is completely controlled by isolation from the surrounding hydrologic régime are called "polders". These areas are not traversed by external water courses and the run-off can be controlled. In South-East Asia polders have been built in the Sunderbans in India and East Pakistan and in certain localities of the coastal zone of the Irrawaddy, Chao-Phya and Mekong deltas (*casiers hydrauliques.*)

Impoldering is an absolute necessity for urban areas in deltas (Bangkok in Thailand, Hanoi in northern Viet-Nam, Pnomh-Penh in Cambodia) to solve the problems of flood protection, drainage and sewerage.

Hydrologic measurements

There is a general lack of data on the hydrologic and agrohydrologic conditions of the land areas in the deltas. Collection of data for large areas encounters technical difficulties. The work can be reduced by the selection of genuinely representative sample areas. The areas should be selected to be representative in relation to the particular factor requiring study. Data could be collected on rainfall, drainage, evapotranspiration, ground-water levels, salinity conditions, etc. This might also be an item for Unesco's Hydrologic Decade in which the "representative" and "vigil" basins play an important role. An essential requirement is the hydrologic delimitation (embankments and controlled run-off). Agrohydrologic items, such as required spacing of drains, type of irrigation, etc., could also be studied.

An example of such a sample area can be seen in the delta of the Mekong near Soc Trang.

HYDROLOGIC DEVELOPMENT OF DELTAIC AREAS IN THE HUMID TROPICAL ZONE

It has been shown above that the hydrologic conditions determine to a large extent the hydraulic works and the type of land utilization, at least in the early stages of technical development. A certain progressive development can be seen in which the nature of the first step is dictated by the specific hydrologic conditions of the deltaic area concerned followed by steps which are similar to those in other areas.

The various stages of development are given below.

Occupancy of natural ridges such as natural river levees, present and former beach lines. This type of occupancy can be seen locally in those deltaic areas in the humid tropical zone where no adequate water control has been provided (e.g., in the lower reaches of the deltaic area of the Irrawaddy); it is still the prevailing type in the deltaic area of the Niger.

Opening up of the area by canals. To make the deltaic area accessible and to allow human settlement, canals are dredged, the spoil being dumped on the banks. Houses are built as linear settlement on these low artificial ridges. Works of this type were carried out towards the end of the nineteenth century in the deltaic area of the Chao-Phya and to a very large extent in the Mekong delta.

The alignment of these canals is not always suitable for drainage purposes.

Spreading of the river floods over the various distributaries. This may be under appropriate conditions a first step for control in the area of the river floods. A typical example is provided by the Chao-Phya where the effect of the river floods has been moderated

or partially controlled by a system of diversion dams, regulators and canals in addition to the natural detention basins. The main diversion dam is located at Chainat near the apex of the delta. From there the flood-waters can be sent through various distributaries and spread further downstream. Diversion of water and use of spillways is also applied in other deltaic areas (Pampanga, Luzon, and River Tone in Japan).

Partial flood protection by open embankments. This system has been applied in the deltaic area of the Irrawaddy (see Fig. 1 of the author's article in Part VI). Embankments have been built which encircle the areas between the river branches at the upstream end but leave the downstream ends open to the floods (open or horseshoe embankments). Another system of partial flood protection is found in the Pampanga delta (Fig. 5).

Canals in the land areas for drainage purposes. To facilitate the drainage of the land areas to the rivers or the sea canals are dredged for the collection of excess water. In order to prevent the outer water from entering and to apply water conservation when required, the outfalls are equipped with movable gates.

This system is a first step towards adequate water control of the land areas. It has been applied among others to a large extent in the Sunderbans area in India and East Pakistan and in the Chao-Phya area.

Adequate flood protection by closed embankments. Closed embankments are an absolute necessity in the tidal zone of a deltaic area where the land would be flooded during storm surges or exposed to salt-water intrusion by exceptionally high tides. Closed embankments can be seen in all deltaic areas where land is used for agricultural purposes in the tidal zone even when no adequate flood protection has been provided in the upper portions of the deltaic area.

For the upper portion of the deltaic area closed embankments are required when the floods are flashy; the floods would cause heavy losses if there were no dikes. Thus in the deltaic area of the Red River (northern Viet-Nam) dikes were built many centuries ago and the policy of "keeping up the dikes" has always been pursued. The same applies to the deltaic areas in Japan.

As stated previously the deltaic areas in the humid tropical zone with gentle flood rises and falls offer many examples of agricultural use in the absence of adequate flood protection. This, however, is a prerequisite to adequate water control of the land areas and to the introduction of modern farming practices.

Adequate water control in the land areas. In a further stage of the technical development the system of water supply by the flood-waters in combination with water conservation is replaced by a system of controlled supply. This supply is either a supplementary irrigation in the wet season or an irrigation in the dry season. The deltaic areas in Japan and China (Taiwan) offer many examples of adequate water control. The system provides a complete flood protection as well as drainage and irrigation facilities either by gravity or by pumping. The same applies to some horticultural districts to the west of Bangkok in the Chao-Phya delta.

Water control measures in the upstream portions of the river basin. By the construction of reservoirs in the upstream portions of a river basin the flood peaks can be reduced and the minimum flow can be increased. This is of primary importance for rivers with flashy floods and low dry weather flows (Japan, China (Taiwan)).

The construction of dams in the upper catchment of the Chao-Phya, which has gentle floods, will also benefit the downstream areas.

Résumé

Hydrologie superficielle des régions deltaïques (A. Volker)

On définit généralement l'hydrologie comme l'étude interdisciplinaire de la présence et des mouvements de l'eau sur et sous les terres du globe. Pour des raisons pratiques, on étudie à part les eaux de surface, bien que cette étude soit étroitement liée à celle des eaux souterraines. Ce rapport est particulièrement étroit dans le cas des régions deltaïques, où le niveau des eaux souterraines est proche de la surface.

L'hydrologie superficielle des régions deltaïques présente certains caractères qui la distingue de l'hydrologie superficielle du bassin supérieur du fleuve. Cette différence est due aux facteurs suivants :

a) La faible pente du fleuve et de sa vallée;
b) Les effets des marées sur le cours du fleuve et l'apport d'eau salée provenant de la mer;
c) Le réseau des bras et des ramifications du fleuve;
d) Les modifications rapides qui peuvent se produire dans la configuration du lit du fleuve;
e) La faible élévation des régions riveraines.

Les processus hydrologiques de base sont à peu près les mêmes dans toutes les régions deltaïques des diverses zones climatiques. Dans les régions deltaïques de la zone tropicale humide, les conditions hydrologiques sont caractérisées par l'élévation du taux de précipitation et d'évaporation en fonction de la mousson, par le type de crue et par le fait que, pour la plupart, les deltas de la zone tropicale humide sont encore à un stade rudimentaire de développement technique.

L'auteur traite à la fois de l'hydrologie du lit principal et des bras du fleuve et de l'hydrologie superficielle des régions riveraines, qui sont liées de manière particulièrement étroite dans les deltas où l'aménagement hydraulique n'est pas encore suffisant. En période de hautes eaux du fleuve et en période de forte marée, les terres risquent d'être inondées; le drainage des terres dépend de l'état du fleuve; l'apport d'eau salée dans le fleuve influe sur l'état de salinité des terres, etc. Les régions deltaïques du Gange (Inde et Pakistan-Oriental), de l'Iraouaddi (Birmanie), du Chao-Phya (Thaïlande), du Mékong (Viêt-nam), du Pampanga (Luzon-Philippines), que l'auteur étudie brièvement, fournissent de nombreux exemples de l'interdépendance de l'état hydrologique du fleuve et des terres riveraines, laquelle influe considérablement sur l'utilisation des terres pour l'agriculture.

Ce rapport est moins étroit dans les régions deltaïques où des mesures techniques de défense contre les crues et d'aménagement des eaux ont été prises; les deltas des fleuves japonais, qui font également l'objet d'une brève étude, en fournissent des exemples caractéristiques.

L'intervention de l'homme dans l'état hydrologique de telle ou telle partie d'une région deltaïque peut avoir des répercussions sur l'état d'autres parties. C'est là un autre caractère distinctif de l'hydrologie superficielle des régions deltaïques.

Discussion

F. R. Fosberg. Would it not be advisable also to set aside further areas in the more undeveloped deltaic areas, not to be experimented with but to be preserved in their original condition for comparison with the developed areas, to judge the programmes value of the development and to provide an opportunity for future scientists to study the delta areas as they were before all these engineering works took place?

A. Volker. I fully support Dr. Fosberg's idea and should like to recommend (a) the implementation of experimental or pilot polders in deltaic areas for detailed agrohydrological and agricultural investigations and (b) the preservation of virgin areas to enable further study of the original conditions.

L. Huisman. Water resources management consists of two parts: water quantity management and water quality management. It may be that in humid tropical deltas in the first stage of technical development, the quality of the water is of less importance, but it is of the greatest importance in highly industrialized regions such as the basins of the Rhine, the Ohio, etc. Also in humid tropical deltas industrialization will occur and it is therefore of the utmost importance to keep a close check on the development, that is the deterioration, of water quality. In this respect it is proposed that, along with the collection of hydrological data, regular measurements in water quality be made.

Significant changes of river régime due to delta growth

Boonchob Kanchanalak

INTRODUCTION

The delta of the River Chao-Phya is raising and extending seawards and this will probably continue for an indefinite time due to the deposition of millions of tons of earth carried by the river. While this process provides additional land at the head of the delta, human welfare over the fertile land adjoining it is also affected by the increasing rate of flood inundation. If the Gulf floor were low enough to allow space for deposit and the sea current strong enough to disperse the silt to places other than the original outlet, the gradient and consequently the bed and the flood levels would not be affected. But the Gulf of Thailand is relatively shallow; the extension of the outlet thus causes a flattening of the gradient and subsequently a rise of the river bed. Consequently it raises the flood level. The behaviour of the Chao-Phya and of its delta can be seen clearly from Figures 1 and 2.

THE CHAO-PHYA AND ITS DELTA

The Chao-Phya, one of the largest rivers in Thailand, serves as a main source of supply and as a large inland waterway. Bangkok is situated on its tidal reach, about 50 km. from the outfall. The river occupies as much as 160,000 sq. km. of catchment basin, covering 31 per cent of the country, and carries the average annual peak flow of nearly 4,000 cu. metres per sec., handling about 31,000 million cu. metres of run-off

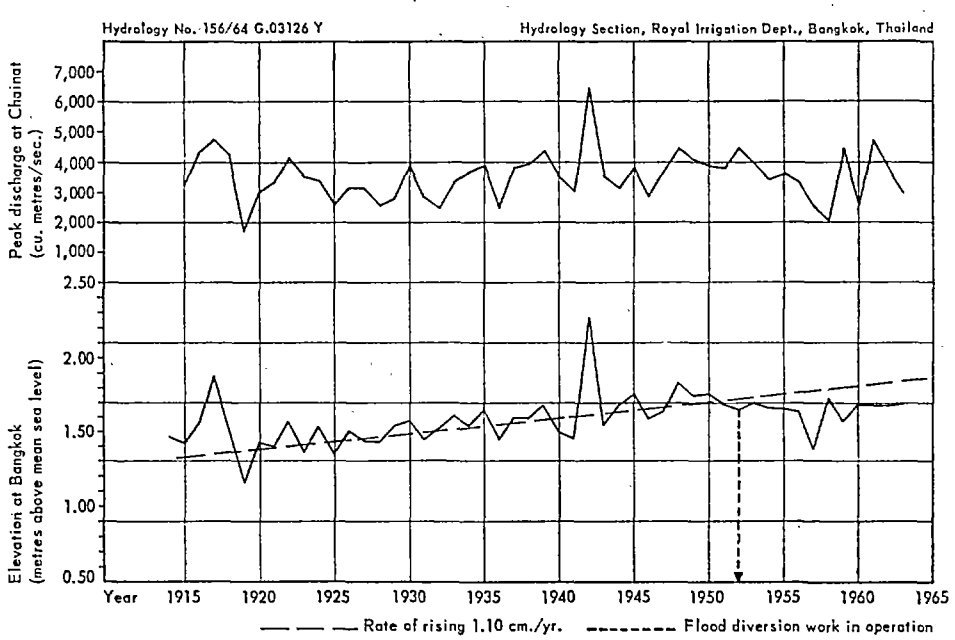


FIG. 1. Rising of annual flood level of the Chao-Phya at Bangkok due to outfall extension of Chao-Phya delta.

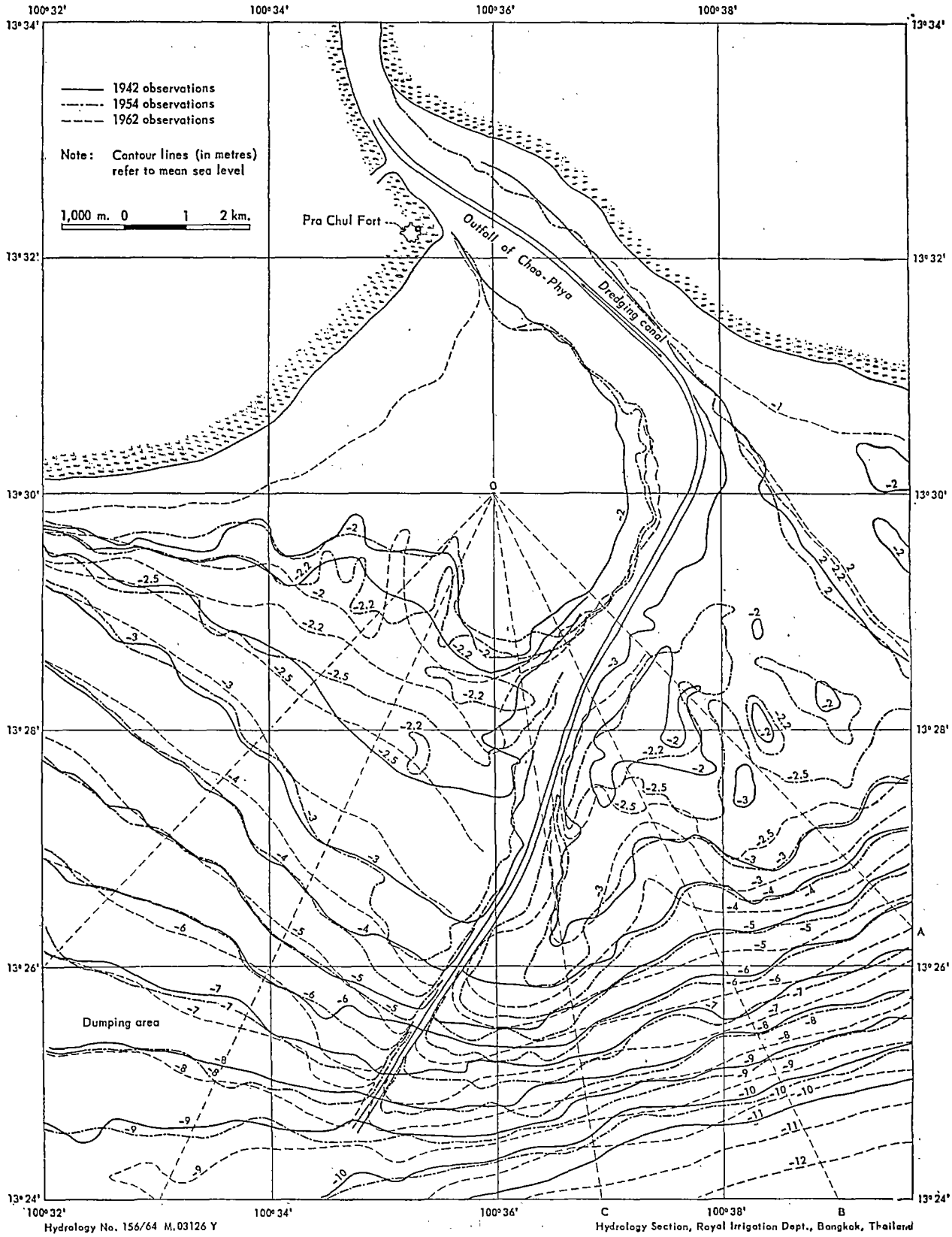


FIG. 2*a*. Outfall extension of Chao-Phya delta.

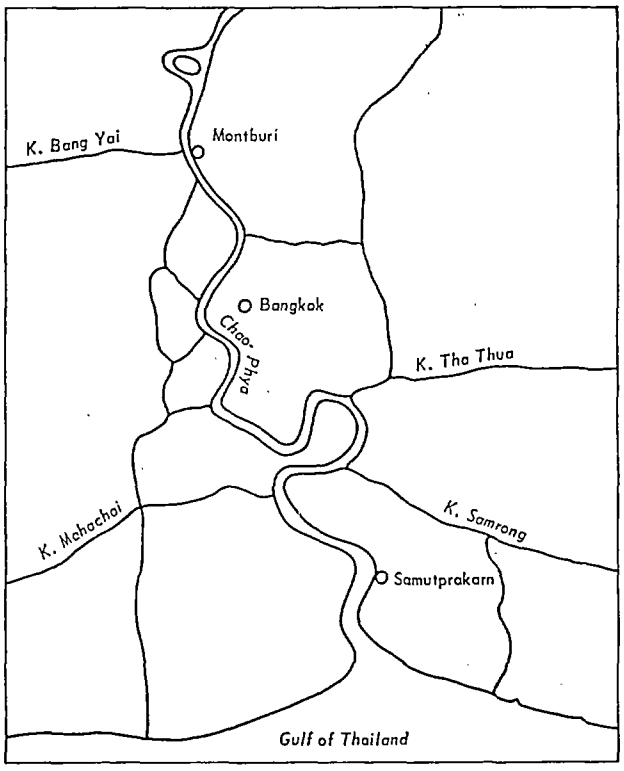


FIG. 2 *b*. Map of Bangkok bar and Chao-Phya estuary.

yearly. Its tributaries have their sources in the mountainous region in the northern part where extensive cultivation and deforestation have been carried out owing to the considerable increase in population. The volume of suspended sediment transported mainly through these tributaries is of the order of 13 million tons per year. The observed data collected at the apex of the river flood-plain delta are shown in Table 1.

TABLE 1. Volume of sediment carried yearly (in millions of tons)

Year	Suspended sediment	Year	Suspended sediment
1949	14.5	1952	9.7
1951	14.7	1953	10.5

It is believed that the mouth of the Chao-Phya was formerly located at the present apex of the river flood-plain delta, 360 km. from the present mouth. The Chao-Phya is an efficient delta-builder which continues to raise and extend seawards the delta based on the upstream erosion, which may be expressed as an annual erosion depth ranging from 0.12 to 0.32 mm.

The flood-plain delta of the river, thus built, extends about 200 km. north from the northern shore of the Gulf of Thailand, having its apex at Nakorn Sawan where the two non-perennial rivers, the tributaries Ping and Nan, unite. The base width along the shoreline is about 100 km. The maximum width is 200 km. located along a line 50 km. north of the Gulf coast. The total delta area including that of the Meklong on the west and the Bang Prakong on the east is nearly 2 million hectares, of which 1.6 million hectares are under diversion irrigation. As regards the submerged delta at the river mouth, the map shown in Figure 2 illustrates the sediment transportation and deposition of the Chao-Phya.

OBSERVATIONS

During the wet monsoon season, flood-water rushes down the river, over-flowing its banks to flow through the flood-plain, and eventually finds its outlet interfered with by the tide at Bangkok. The annual maximum flood levels observed for the last 50 years at Bangkok indicate a fascinating rising trend at a constant rate of 11 cm. per decade, as clearly seen in Figure 1, while the long-term inflow flood magnitudes observed at the apex of the flood-plain delta still maintain their general normality. Since 1952, however, the flood inundation level has stopped increasing due to the rotational spreading of flood-water over various distribution systems through diversion works, a means of flood control adopted in this country.

Rise of the river bed to an appreciable degree is also detected along the Bangkok profile, as clearly illustrated in Figure 3.

DELTA EXTENSION

Analysis of the movement of the delta at the river mouth reveals the inconsistency of the extension with respect to time. It may depend on various factors,

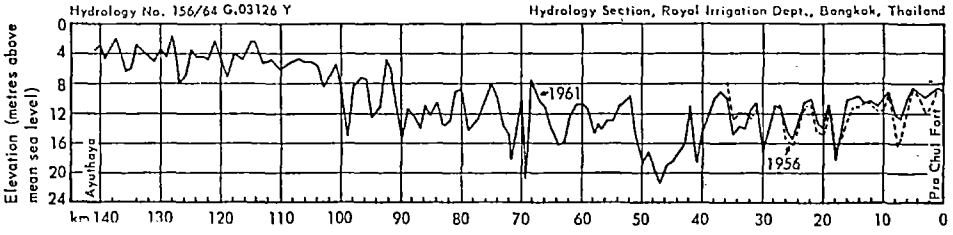


FIG. 3. Profile of deepest section of the Chao-Phya from Ayuthaya to outfall.

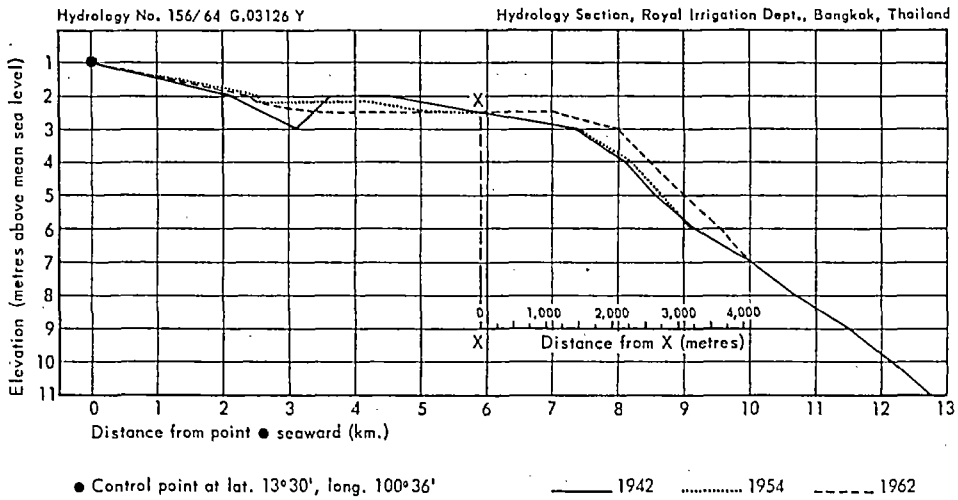


FIG. 4. Outfall extension of Chao-Phya delta profile along section OA observed in 1942, 1954, and 1962.

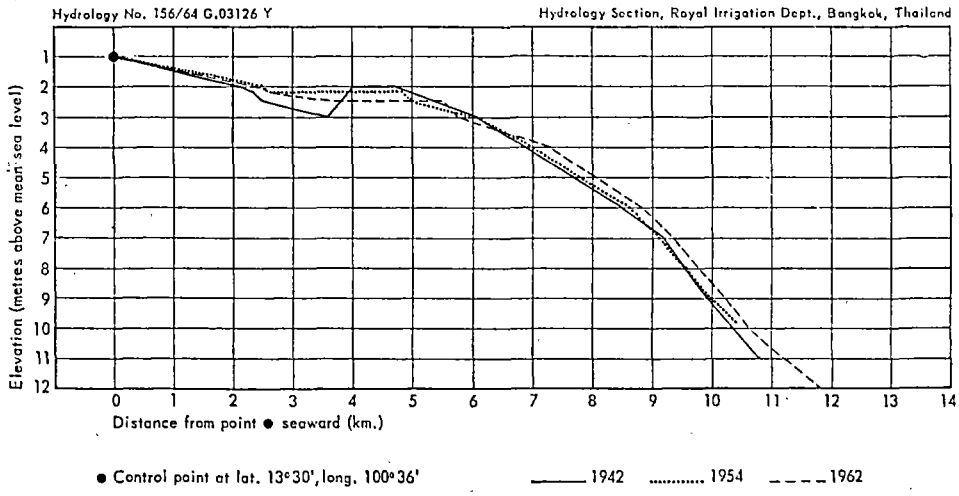


FIG. 5. Outfall extension of Chao-Phya delta profile along section OB observed in 1942, 1954, and 1962.

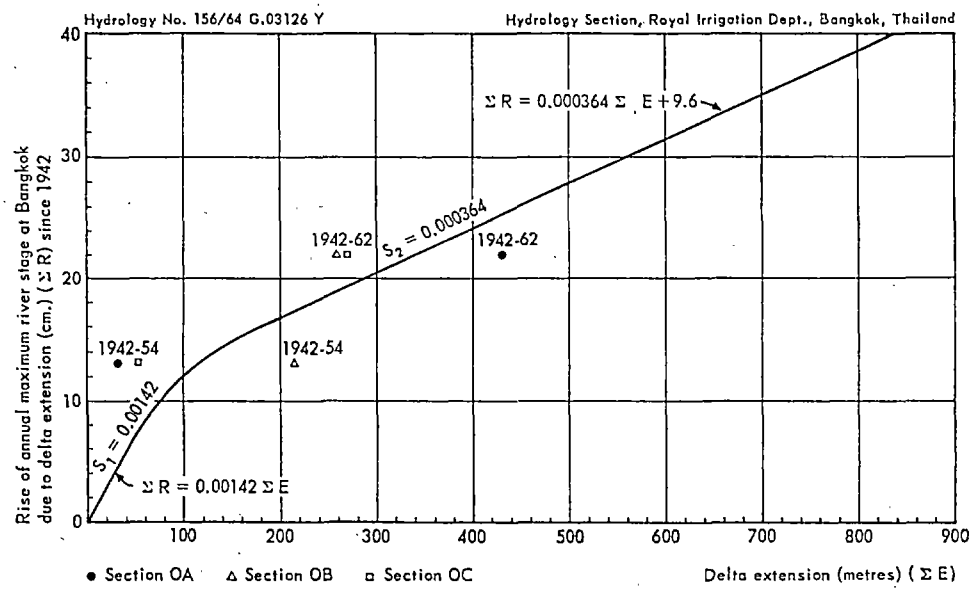


FIG. 6. Double mass analysis of rise and delta extension of the Chao-Phya.

variations in the amount (millions of tons) of silt transported presumably being one of the significant factors. But the mould of the delta definitely indicates that some extension and raising has prevailed from time to time. The growth of the delta has been detected from a comparison between series of representative cross-profiles. The weighted mean extension varied from 250 metres to nearly 500 metres during the last 20 years. The information on the silt rate at Bangkok, the types and sizes of materials deposited at the delta are not available.

Double mass plotting of the rise and the extension indicates a relatively short extension occurring during the 12 years from 1942 to 1954, whereas an active extension has occurred since 1954 (Figs. 4 and 5).

RELATIONSHIP BETWEEN RISE OF ANNUAL FLOOD LEVEL AND DELTA EXTENSION

By the general basic law that governs the river régime, $Qs.d \sim Qw.s$, where Qs is bed-load sediment flow, d is bed material size, Qw is river flow with gradient s, a higher rate of silt deposition should take place when the gradient becomes less due to delta extension, resulting in the rise of the river bed as well as the stage. Assuming that the adaptation of the river gradient takes place simultaneously with the delta extension, the rise R of the bed would be proportional to the product of the extension E and the river régime s or, $R \approx Es$.

Double mass correlation between rise of flood levels and delta extensions, illustrated for the Chao-Phya in Figure 6, indicates a sudden decline in slope of the correlation line from 0.0014 to 0.000364 for the period 1942-54 to 1954-62, which raises the question of whether it is affected by time lag between R and E or other discrepancies.

Assuming that the relationship during the period 1954 to 1962 continues for some time, the results shown in Table 2 may be expected.

TABLE 2

Further seaward delta extensions (E) (metres)	Rises of flood level in Bangkok (R) (cm.)	Years from 1964
100	3.64	3
200	7.28	7
300	10.92	10
400	14.56	13
500	18.20	17

It may be concluded that, during the next 35 years, if there is no improvement in control, the flood level at Bangkok will rise by 2 metres or more and the submerged delta will have grown about 1 km. in length. This is a fascinating figure because Bangkok rests on an elevation of only + 2.00 metres while the present flood level is 1.65 to 1.70 metres.

Résumé

Modifications importantes de l'hydrologie d'un fleuve dues à la progression du delta à son embouchure (Boonchob Kanchanalak)

La présente communication met en parallèle la progression du delta du Chao-Phya à son embouchure et l'élévation du niveau de crue depuis cinquante ans dans la zone soumise à l'influence des marées, à Bangkok. La conclusion est un net avertissement à la ville de Bangkok.

Le niveau de la crue annuelle s'élève en moyenne de 1,10 cm par an, et la progression du delta à l'embouchure a été de près de 500 mètres en vingt ans le long de certaines sections. Il semble que l'élévation du lit du fleuve explique assez bien le phénomène.

L'auteur se fonde principalement sur des données assez récentes en ce qui concerne la progression du delta, mais sur une longue période d'observations systématiques en ce qui concerne les niveaux des crues.

L'analyse de l'influence de la progression du delta sur le niveau de la crue annuelle du Chao-Phya à Bangkok montre qu'il y a un certain délai entre la progression et l'élévation de niveau qui en résulte.

Discussion

F. R. Fosberg. In view of the continuing extension of the delta, it would seem that the spreading out of the water over the Bangkok plain is only a temporary measure. If the erosion rate mentioned in the drainage basin continues, the delta extension will continue and the plain will become saturated. Would not a more logical approach be to encourage reforestation of the eroded areas and reform of agricultural practices to cut down this erosion and the extension of the delta, and thus alleviate the increase in flooding?

Boonchob Kanchanalak. Impounding dams and reforestation in the river catchment are under way.

S. N. Naqui. Rainfall should be taken into consideration in studying the rise of flood level.

Boonchob Kanchanalak. There is an indication that the flood magnitude gives no effect to the flood rising trend as already mentioned in the paper. Rainfall, which is the controlling factor of flood magnitude, therefore, has nothing to do with the rising trend.

V. N. Nagaraja. The author has endeavoured to study the trend of the extension of the delta and the consequential changes in the river régime of the Chao-Phya and has deduced that in the coming years the rise in flood levels on account of the rise in the river-bed level would be alarming as far as Bangkok is concerned.

As has been observed by the author, the trend improved after 1952 on account of drainage and flood control measures. These measures will doubtless continue. There will also be the natural factor of subsidence at the river mouth which will restore, at least partly, the present régime slopes. These things considered, it would appear that the threat to Bangkok would be much smaller than anticipated in the paper. For studying the behaviour of the bed levels, loss water may be analysed for as many years as possible.

Boonchob Kanchanalak. Other phases of the study rather than that described in the paper will be continued.

Ground water in deltas

L. Huisman

INTRODUCTION

Ground water is defined by Meinzer as water that occurs beneath the surface of the earth in the zone of saturation where it fills the interstices, joints, crevices, fissures, solution holes and any or all other voids. The amount of ground water in a specified area consequently depends on the thickness and porosity of pervious formations and on the depth of the water table, factors which vary from one region to another. Averaged over the entire land surface of the earth, ground-water reservoirs contain fresh water to the amount of roughly 100 million cu. metres per sq. km.

Ground water as defined above, however, is not a separate body of water the occurrence and movement of which may be studied by itself. Ground water only constitutes one portion of the earth's water. This water, as water vapour in the atmosphere, as surface water in streams, lakes, seas and oceans and as ground water in the interstices of the subsoil, is in a continuous circulatory movement. There is a never-ending transformation from one state to another known as the hydrologic cycle (Fig. 1). Water from the atmosphere falls to the ground as rain, hail, sleet and snow and condenses above ground as well as in the openings of the earth's crust. Part of this water is returned to the atmosphere by evaporation and transpiration, another part travels over the ground surface to streams and lakes and the remaining part moves further downward through the upper strata until it reaches the ground-water table and recharges the ground-water supply. This ground-water is not stagnant but flows through the soil in the general direction of the slope of the ground-water table. Sooner or later this ground water appears again at the surface, visible in the form of springs and invisible as ground-water overflows in rivers and lakes. The smaller streams combine to form larger rivers which carry the water to the sea. Here evaporation returns the water to the atmosphere and the cycle begins once more.

According to the hydrologic cycle, the amount of ground-water in a particular aquifer increases continuously by downward percolation of surface water from precipitation and natural infiltration from streams and lakes. At the same time this aquifer loses ground water by evaporation and perhaps even transpiration, by overflows in surface streams and by percolation to neighbouring aquifers through separating semi-pervious aquicludes (Fig. 2). In the long run inflow equals outflow and a stationary water table occurs, seasonal

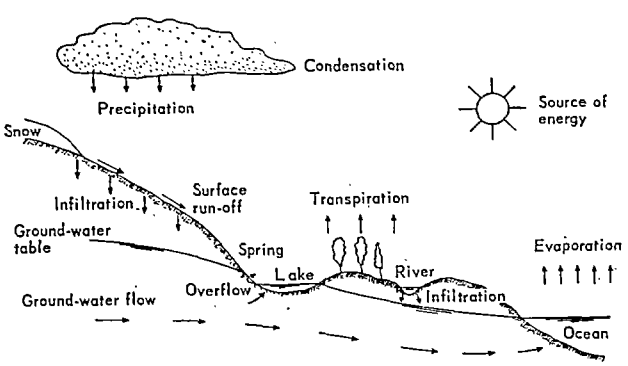


FIG. 1. The hydrologic cycle.

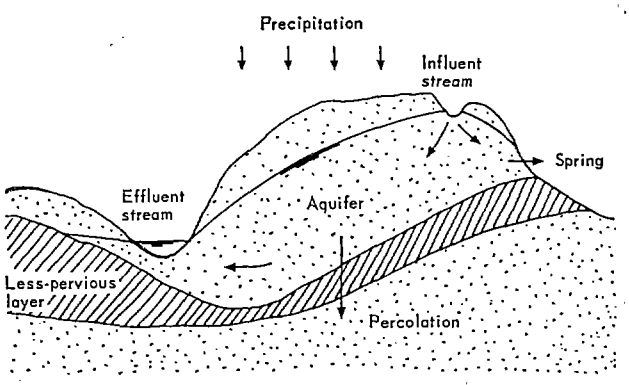


FIG. 2. The ground-water cycle.

variations only resulting in fluctuations around the average level. The amount of inflow equal to outflow again varies from one area to another, depending on the magnitude of the available rainfall (that is rainfall minus the losses due to evapotranspiration) and on infiltration opportunities. Over the entire land surface of the earth, the average value equals 0.2 million cu. metres per sq. km. of surface area. Incidentally this means an average detention period of 500 years!

By human interference the ground-water cycle is often influenced to a large degree, raising or lowering the average water level. All over the world large amounts of ground water are recovered for drinking and industrial water supplies, for irrigation, as cooling water, etc. When ground water is abstracted from an aquifer by artificial means, a lowering of the water table will occur, increasing recharge and decreasing discharge. Recharge increases by a shift of the water divide, enlarging the catchment area, and by a larger infiltration of surface water. The discharge decreases by a reduction of evapotranspiration and decreases or even becomes negative by a smaller return of ground water to the surface and by less percolation to bounding aquifers. As long as the amount of artificial abstraction is limited, the resulting increase in recharge together with the decrease in discharge is able to balance this abstraction and a new equilibrium situation arises. The maximum possible abstraction reduces the outflow to zero and brings the amount of water entering the aquifer up to the highest value obtainable under the geohydrologic conditions present. Any larger abstraction is partly taken from storage, continuously lowering the ground-water table and allowing such an abstraction for a limited (though often long) period only. The maximum permissible ground-water abstraction, the safe yield of the formation, is only part of the maximum possible one. It occurs when the accompanying lowering of the ground-water table becomes objectionable or the increase in catchment area together with reversal of outflows attracts water with undesirable chemical or bacteriological characteristics, endangering the quality of the water recovered.

The reverse of artificial abstraction is artificial replenishment with opposite results, raising the average water level, augmenting ground-water outflows and decreasing the amount of natural infiltration. Artificial replenishment is a necessity when more ground water is required than the maximum permissible abstraction under natural conditions. Overpumping the aquifer with all its detrimental effects may now be avoided by a simultaneous artificial increase of the amount of water entering the aquifer. This increase can be effected: (a) directly by spreading surface water over pervious soils in basins, ponds or ditches and by flooding or by injecting the water with wells, shafts or pits (artificial recharge); (b) indirectly by locating the means for ground-water abstraction close to surface streams with pervious banks. The lowering of the ground-water table accompanying abstraction will now result in an increased inflow of water from such streams (induced recharge).

In this way artificial replenishment is also able to maintain ground-water levels at existing conditions, for instance to prevent subsidence of foundations by dewatering a building site nearby and to raise ground-water levels above existing conditions, for agricultural purposes, for pushing back salt-water intrusions, to prevent inflow of polluted water, etc. Artificial replenishment is also applied to make full use of the capacity of the aquifer to filter, to store and to transport water. By means of artificial replenishment it is possible to transform surface water with varying characteristics into ground water of constant quality, safe as a public supply; to store surplus water in wet periods for subsequent use in dry periods; to transport water from the point of replenishment to the point of abstraction, especially useful when recharge can be effected at one or a few spots and abstraction occurs locally, in a larger number of sites; to reduce the amount of surface water for flood flow protection, storm drainage, etc., or to dispose of surface water with undesirable characteristics, such as domestic and industrial wastes, etc.

Hydrology is the science of the occurrence and movement of water over and under the earth's surface from the moment of precipitation to the moment of entry into the ocean or of evaporation into the atmosphere. Ground-water hydrology is only part of this science. For practical reasons the ground-water aspects of deltaic areas are treated separately in this paper. From the foregoing it will be clear, however, that a close relation with the conditions of the surface water exists. This is especially true in deltas where pervious formations with ground water at a shallow depth below the surface are the rule rather than the exception.

SPECIAL ASPECTS OF GROUND-WATER HYDROLOGY IN DELTAS

Qualitatively, the ground-water cycle as described in the preceding section is exactly the same for deltaic areas as for any other region in the world. In deltas, also, the supply, flow and discharge of ground water follow common hydrologic laws. Quantitatively, however, many differences can be noted, while the presence of the sea with its tidal fluctuations and its higher salt content provides an added complication. The propagation of tidal fluctuations and the intrusion of salt and brackish water in coastal aquifers will be treated separately in the subsequent sections.

As main characteristics of deltas may be mentioned the small differences in ground-surface elevation, usually only a little above the level of the bounding streams, and the composition of the subsoil, built up of unconsolidated sedimentary deposits of high porosity down to great depths. By their origin, these

deposits are more or less horizontal, while semi-pervious layers of clay and peat alternate with pervious layers of sand and gravel. Consequently there is not a single water-bearing formation, but many (artesian) aquifers can be distinguished. With the small slope of rivers and land areas, the piezometric level of the artesian water will vary only little with depth. In exceptional cases confined aquifers stretch over considerable distances and have outcrops on the mainland proper, at a higher altitude. The level of the artesian water may then rise above ground surface and wells drilled here will be flowing artesian wells.

The sedimentary water-bearing formations in deltas usually have a high specific yield and a high coefficient of transmissibility. Large amounts of ground water can thus be transported with a small slope of the piezometric surface only. Deltas, moreover, are crossed by an intensive network of river branches and ramifications, limiting the lateral travel of ground water. Because of these two factors the change in water-table elevation going from one end of the aquifer to another will be small and an abundant supply of ground water will be present. The change in ground-water levels with time depends primarily on the variation in the water levels of the bounding streams and also on the fluctuation in available rainfall and the amount of artificial interference.

In temperate climatic zones the variation in the amount of available rainfall in the course of the year is limited. In the lower region of the delta, the variation in the water levels of the bounding streams averaged over a number of days is also small and here ground-water tables will fluctuate only little with time. Together with the low elevation of ground surface this means that in these areas ground water is present at a shallow depth below the surface, allowing an intensive use of this water for agriculture and many other purposes. Protection against the sea, however, is necessary to prevent flooding with salt water. In the intermediate and upper regions of deltas in temperate climatic zones, variations in river levels during the course of the year are appreciably larger and here ground-water tables may fluctuate considerably. In highly developed deltas drainage in wet and irrigation in dry periods is often practised to keep water-table fluctuations within acceptable limits. This may also be necessary because in such deltas large amounts of ground-water are often abstracted for drinking and industrial water supplies, for irrigation, as cooling water, etc. As these amounts increase, the natural outflow of ground-water to the bounding streams will first reduce and then reverse. With the high capacity of the aquifers to transport water and the constant scouring of river bottom and banks, the fall of the ground water table farther inland will still be small and adverse effects on the agricultural use of the land concerned may be negligible. With greater abstractions, an excessive lowering of the ground-water table would occur and artificial ground-water replenishment, mostly by surface spreading methods, must be employed to keep water levels above the minimum allowable ones.

In humid tropical zone deltas not only the total amount of rainfall but especially the variation in the amount of available rainfall from the wet to the dry season is appreciably larger than in temperate climates. Considered by itself, this means a larger variation in water-table depth from one place to another and from one season to the other. This variation must again be augmented with the variation in the water level of the bounding streams. In the upper and intermediate regions of humid tropical zone deltas, the last-mentioned variations are large and because of both factors together ground-water elevations here will show very great fluctuations. In the wet season the aquifers have to transport huge amounts of rainfall excess to the bounding streams where this ground water can only be discharged at a high level. The water table farther inland will rise accordingly and in deltas in their original natural state flooding will occur. In the dry season recharge by rainfall is negligible and the aquifers may even lose large amounts of water by evapotranspiration. Flow reversals occur, the aquifer now being supplied by surface water infiltrating through the banks of the bounding streams. In the dry season this surface water is at a low level. Water-table depths farther inland will still be lower and usually at such a depth below ground surface that this ground water is of little use for agricultural purposes. Flooding in the wet season is not an obstacle to farming, but larger returns could be obtained with a better system of water control, with dikes to confine the surface water between the banks of the river and with a system of drainage to dispose of the rainfall excess. Farming in the dry season requires irrigation, usually with surface water taken from the bounding streams. For smaller plots, especially at a greater distance from surface water, irrigation with ground water recovered by wells will be cheaper and easier to realize for the individual land owner. For larger plots ground-water irrigation is initially more expensive, but it further depletes aquifers in dry seasons, providing more storage for excess water in wet periods. When, in highly developed areas, flooding in wet seasons is prevented and large amounts of ground water are also abstracted for various purposes, the natural recharge of the ground-water supply may become insufficient and must then again be augmented by artificial replenishment.

In the lower part of the delta, near the sea, also in humid tropical areas, the water levels in the bounding streams depend on sea level and will vary little from dry to wet seasons. Consequently ground-water levels will change less with time. Flooding is now the result of a raising of the sea level, covering the land areas with salt water and making them unfit for agricultural use for many years. Even in deltas in the first stage of technical development, protection against

this flooding must be provided if a profitable use of these areas is to be made. In dry seasons the inflow of surface water into bounding aquifers will still consist of salt water. This does not need to be objectionable as long as the land surface is far enough above mean sea level to flush these salt-water intrusions away in wet periods. With the surface of the land protected by embankments below mean sea level a continuous inflow of salt water occurs. This salt water will finally percolate upward to the zone of aeration where it mixes with fresh water from rainfall. With deep drainage the damage done to agriculture in wet periods can be minimized, while in dry periods irrigation is necessary for dilution. For this irrigation only ground water is now available, taken from fresh-water lenses below impervious or semi-pervious aquicludes.

In deltas, an abundant supply of fresh water is present in the rivers that cross the area and in the first stage of technical development there is little need for ground-water abstraction. For domestic use only, to obtain water bacteriologically safe and to obtain fresh water in those lower parts of the deltas where the surface water is salt or brackish, small amounts of ground water are recovered, amounts so small that an influence on the ground-water cycle is negligible. In highly developed deltas large amounts of ground water are needed for irrigation, for industrial purposes, as cooling water, etc. To prevent difficulties arising from such large abstractions, a careful analysis of the ground-water resources available is necessary, so as to be able to predict with accuracy the results of any proposed abstraction. This analysis follows common rules. Special attention, however, must be paid to the presence of salt water in the subsoil and the close contact between ground water and surface water in the many river branches crossing deltaic areas.

Generally, fresh water floats upon underlying salt water with a rather sharp boundary between the two types of water. Above this boundary only fresh water and below it only salt water is present, while the depth of the fresh-salt water interface depends on the distance to which the piezometric level of the fresh water rises above that of the salt water. With salt water at rest, as it normally is, and its piezometric level constant, fresh water is present to greater depths as the piezometric level of the fresh water is higher, that is at greater distances to the bounding seas and estuaries. To this general rule there are, however, many exceptions and in coastal aquifers a rather random variation of salt content with depth may occur. On the one hand this is due to the presence of impervious and semi-pervious layers, allowing salt-water wedges to penetrate far inland or freshwater tongues to stretch over considerable distances below the bottom of the sea (see below, "Flow of Ground Water in Coastal Aquifers"). On the other hand this is the result of historical development, changing hydrologic conditions and flushing away pore water present in the sediments at the time of deposition. Now, when such sediments are enclosed by less-pervious layers, flushing is retarded or even completely prevented and the original pore water may still be present. In this way salt-water pockets may be found in an otherwise fresh aquifer and freshwater pockets in an aquifer completely intruded by salt water. These fresh and salt-water pockets escape any mathematical calculation and their presence is always a surprise, usually an unpleasant one. Except for cooling purposes, no profitable use can be made of salt ground-water and its presence always limits abstraction of the overlying fresh water. When analysing ground-water resources, the occurrence of salt water should therefore be determined with accuracy. Its presence must also be taken into account when measuring ground-water levels and comparing them for the purpose of determining magnitude and direction of flow.

Where a stream with pervious banks cuts an aquifer, a close contact between ground water and surface water is present. This contact limits the lateral travel of ground water, preventing ground-water tables farther inland from attaining excessive elevations. On the other hand, however, ground-water tables will fluctuate with the water levels in the bounding streams and in dry periods ground-water levels will drop excessively. This close contact only lasts as long as an outflow of ground water occurs (effluent stream). An inflow of surface water accompanying artificial ground-water abstractions (influent stream) will result in a clogging of the river bottom and banks and at the point of contact the ground-water table will fall below the level of the stream. During flood flows this clogging may be scoured away and the free contact restored, but in dry periods a lowering of the water table farther inland cannot be prevented.

The selection of the means best suited to artificial ground-water abstraction in deltaic areas again follows common rules. With regard to the sedimentary character of the unconsolidated formations, vertical wells should be provided with a large diameter artificial gravel pack. For aquifers of limited thickness, the use of radial collector wells is well worth considering. If the fresh water to be recovered is in direct contact with underlying salt water, local drawdowns accompanying point abstraction should be avoided as much as possible. Instead of a few wells pumped at high rates, lines of smaller wells or even galleries must now be used to prevent trouble by upconing of salt and brackish water as much as possible. Still better results may be obtained by choosing a location where an impervious or less-pervious layer separates fresh and salt water. Even when this layer is of limited extent only, it will spread the abstraction over a larger area, reducing drawdown and thus decreasing the danger of attracting saline water (see below, "Salt and Brackish Water Coning").

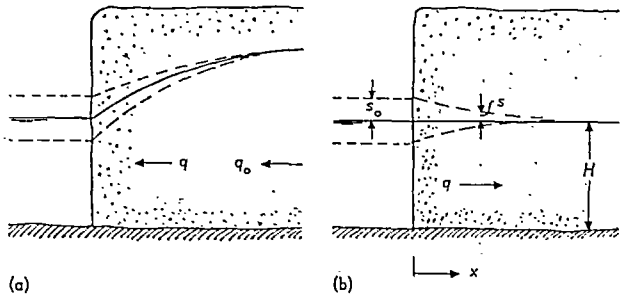


FIG. 3. Propagation of tidal fluctuations in unconfined aquifers.

For artificial ground-water replenishment, deltaic areas with their close contact between ground water and surface water, are favourable for the application of induced recharge. When this induced recharge involves difficulties due to clogging of the stream bottom, variations in water quantity and water quality accompanying changing water levels in the bounding streams, etc., the fully controlled surface spreading methods of artificial recharge will give excellent results. Injection of surface water with wells into sedimentary deposits requires an intensive and expensive pre-treatment of this water, economically justified in exceptional cases only.

PROPAGATION OF TIDAL FLUCTUATIONS

Tidal variations in the level of open water bounding a semi-infinite unconfined aquifer (Fig. 3a) will periodically impede and accelerate the outflow of ground water. Ground-water levels in this aquifer will consequently show a similar tidal fluctuation. When the magnitude s of the resulting changes in water-table depth is small compared to the saturated thickness H of the aquifer, superposition is permitted. For the calculation of these fluctuations the steady-state outflow of ground water q_o may thus be left out of consideration (Fig. 3b) and Darcy's law simplified to

$$q = -kH\frac{\partial s}{\partial x}$$

in which q is the tidal flow per unit width and k the coefficient of permeability of the aquifer concerned. When the water table rises, water is stored in the openings of the formation, while a fall of the water table draws water from storage. With μ as specific yield, the equation of continuity becomes

$$\frac{\partial q}{\partial x} = -\mu\frac{\partial s}{\partial t}.$$

Elimination of q from both equations gives

$$\frac{\partial^2 s}{\partial x^2} = \frac{\mu}{kH}\frac{\partial s}{\partial t}.$$

With the boundary conditions $x = 0$, $s = s_0 \cdot \sin 2\pi\frac{t}{T}$ and $x = \infty$, $s = 0$, this differential equation has as solution

$$s = s_0 \cdot e^{-2\pi\frac{x}{L}} \cdot \sin 2\pi\left(\frac{t}{T} - \frac{x}{L}\right) \quad \text{with } L = \sqrt{4\pi T\frac{kH}{\mu}}.$$

According to this formula, tides of low frequency (large values of T) penetrate farther inland, while ground-water levels vary less and with greater delay as the distance to the shoreline increases. Variations are decimated when

$$e^{2\pi\frac{x}{L}} = 10 \quad \text{or} \quad x_{0.1} = \frac{2.3}{2\pi}L = 2{\cdot}3\sqrt{\frac{kHT}{\mu.\pi}}.$$

With, for instance, $T = 0.5$ day, $\mu = 0.25$ and $kH = 1{,}000$ sq. metres/day, $x_{0\cdot1} = 58$ metres, that is to say tidal fluctuations in unconfined aquifers are propagated over a short distance only.

With confined aquifers, the saturated thickness is constant, independent of the piezometric level. When also the amount of ground water per unit area of aquifer is not influenced by variations of this piezometric level, tidal fluctuations will propagate at infinite velocity, without any damping. In reality, however, the amount of ground water mentioned above changes by percolation to and from neighbouring aquifers and by compression or decompression of soil and water, retarding pressure changes and decreasing their magnitude.

The semi-infinite leaky artesian aquifer of Figure 4 is situated above an impervious base and overlain by a semi-pervious layer with a resistance c against vertical water movement. Above this layer unconfined water with a constant water table is present, relative to which the piezometric level φ of the artesian water is measured. Again applying the principle of superposition and assuming steady-state flows absent, Darcy's law gives for the tidal flow of confined water

$$q = -kH\frac{\partial\varphi}{\partial x}.$$

When by propagation of tidal fluctuations the piezometric level rises by an amount $\partial\varphi$, the pressure of the water in the pores increases with $\rho g \cdot \partial\varphi$, compressing this pore water and also compressing the soil material. With the total weight of soil and water unchanged, the soil pressure decreases by the same amount, decompressing the soil structure. Per unit area and over the

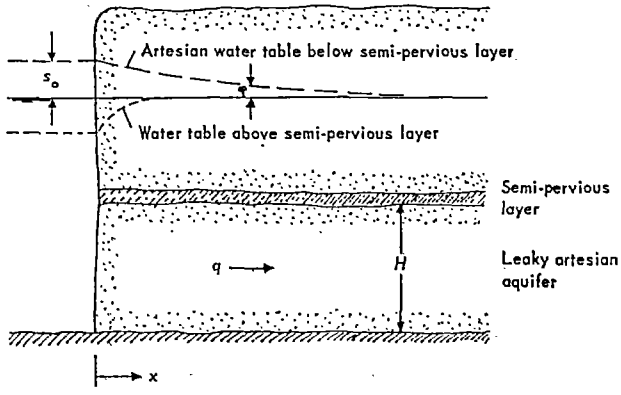


FIG. 4. Propagation of tidal fluctuations in confined aquifers.

full depth of the artesian aquifer, storage space for water thus increases by

$$\frac{\rho g \partial \varphi}{E_w} \cdot p \cdot H + \frac{\rho g \partial \varphi}{E_m} \cdot (1-p) \cdot H + \frac{\rho g \partial \varphi}{E_s} \cdot H = \frac{\rho g \partial \varphi}{E} \cdot H$$

with

$$E = \frac{1}{1 + p \cdot \frac{E_s}{E_w} + (1-p) \cdot \frac{E_s}{E_m}} \cdot E_s$$

and ρ the specific mass density of water, g the gravity constant, p the pore space and E_w, E_m, and E_s the moduli of elasticity of water, soil material and soil structure respectively. Usually E_w and E_m are large compared to E_s and $E \simeq E_s$. With the piezometric level at φ, artesian water is further discharged through the semi-pervious layer to above at a rate $\frac{\varphi}{c}$ per unit area and time. With both influences taken into account, the equation of continuity becomes

$$\frac{\partial q}{\partial x} = -\frac{\rho g H}{E} \cdot \frac{\partial \varphi}{\partial t} - \frac{\varphi}{c}.$$

Substitution of the value of $\frac{\partial q}{\partial x}$ from Darcy's formula gives

$$\frac{\partial^2 \varphi}{\partial x^2} - \frac{\rho g}{kE} \cdot \frac{\partial \varphi}{\partial t} + \frac{\varphi}{kHc}.$$

with the boundary conditions $x = 0$, $\varphi = s_0 \cdot \sin 2\pi \frac{t}{T}$ and $x = \infty$, $\varphi = 0$, this equation has as solution

$$\varphi = s_0 \cdot e^{-2\pi \frac{x}{L_1}} \cdot \sin 2\pi \left(\frac{t}{T} - \frac{x}{L_2}\right).$$

with the values of L_1 and L_2 to be determined from the equations

$$\frac{4\pi^2}{L_1^2} - \frac{4\pi^2}{L_2^2} = \frac{1}{kHc} \quad \text{and} \quad \frac{4\pi}{L_1 L_2} = \frac{\rho g}{kET}.$$

With a fully confined aquifer,

$$c = \infty \text{ and } L_1 = L_2 = \sqrt{4\pi T \frac{kE}{\rho g}}$$

Variations in piezometric level are now reduced to 10 per cent over a distance

$$x_{0.1} = \frac{2.3}{2\pi} L_1 = 2.3 \sqrt{\frac{kET}{\pi \rho g}}.$$

With, for instance, $T = 0.5$ day, $k = 50$ metres/day and $E = 10^8$ kg./sq. metre, $x_{0.1}$ is equal to 2,050 metres, that is to say tidal fluctuations in confined aquifers propagate over large distances. For leaky artesian aquifers, propagation is a little less. With the same data as mentioned above and, for instance, $c = 1{,}000$ days, $H = 20$ metres : $L_1 = 4{,}600$ metres, $L_2 = 6{,}800$ metres and $x_{0.1} = 1{,}700$ metres.

By measuring the propagation of tidal fluctuations in leaky artesian aquifers, the value of the geo-hydrologic constant $\lambda = \sqrt{kHc}$ can easily be determined. In the dune water catchment area of Amsterdam (The Netherlands), it was found that over each 200 metres propagation of tidal fluctuations in the leaky artesian aquifer was retarded by 0.3 hour and reduced by a factor 1.35. This gives

$$2\pi \frac{200}{L_1} = 1 n\, 1.35 \quad \text{or} \quad L_1 = 4{,}200 \text{ metres};$$

$$\frac{200}{L_2} = \frac{0.3}{12} \quad \text{or} \quad L_2 = 8{,}000 \text{ metres};$$

and

$$\frac{1}{\lambda^2} = \frac{4\pi^2}{4{,}200^2} - \frac{4\pi^2}{8{,}000^2} \quad \text{or } \lambda = 790 \text{ metres},$$

somewhat smaller than as found when analysing the results of test pumpings here.

FLOW OF GROUND WATER IN COASTAL AQUIFERS

In coastal aquifers, the seaward flow of fresh ground water comes into contact with salt ground water that has seeped down from overlying bodies of salt water in seas and estuaries. Salt water has a higher specific gravity than fresh water, the difference being from 2 per cent with a chloride content of 16,000 p.p.m., as in many coastal seas, to 2.5 per cent with a chloride content of 20,000 p.p.m., as in the ocean proper where no dilution with fresh outflows from large rivers is noticeable. Due to the higher specific gravity, the pressure of salt water increases more rapidly with depth than the pressure of fresh water and whatever the conditions at the surface may be, from a certain depth downward the saltwater pressure tends to surpass the freshwater pressure, backing up this fresh water till equilibrium is again obtained. In this way a fresh-salt water interface is formed, above which the impeded outflow of fresh water occurs and below which salt water penetrates the aquifer over great distances. Over a limited depth only do coastal aquifers carry fresh water and when ground water is to be abstracted from such aquifers, due consideration should be given to the underlying salt water.

The mathematical description of the simultaneous flow of fresh and salt water in one aquifer follows common rules. For each flow Darcy's law and the equation of continuity hold true, while the piezometric levels of both flows are interconnected by the so-called Ghyben-Herzberg relationship for equal pressures at opposite sides of the interface. With the notation of Figure 5 $(\psi + H) \cdot \rho_s g = (\varphi + H) \cdot \rho_f g$ or $\varphi = (1 + \Delta) \cdot \psi + \Delta \cdot H$ with the relative difference in mass density $\Delta = \frac{\rho_s - \rho_f}{\rho_f}$ between 0.02 and 0.025. With ψ usually small compared to H, this relationship can be simplified to $\varphi = \psi + \Delta \cdot H$. Except in the immediate vicinity of fresh-water outflows, the flow lines are nearly horizontal, the equipotential lines nearly vertical and $\varphi = h$, thus $h = \psi + \Delta \cdot H$.

Where the salt water is at rest and datum line is chosen at mean sea level, ψ is everywhere zero and $h = \Delta \cdot H$ or $H = \frac{h}{\Delta}$. With a hydrostatic pressure distribution (vertical equipotential lines), fresh water in coastal aquifers extends to a depth below sea level of 40 to 50 times the height of the fresh water above this level. When the curvature of the flow lines is taken into account (hydrodynamic equilibrium), this depth is even larger.

Although in many cases a hydrostatic pressure distribution may be assumed, hydrostatic equilibrium is impossible. Differentiating the relation between the piezometric levels at opposite sides of the interface $\varphi = \psi + \Delta \cdot H$ to s gives $\frac{d\varphi}{ds} = \frac{d\psi}{ds} + \Delta \cdot \frac{dH}{ds}$, that is to say, with the boundary plane not horizontal, $\frac{dH}{ds} \neq 0$, at least one of the fluids must be moving.

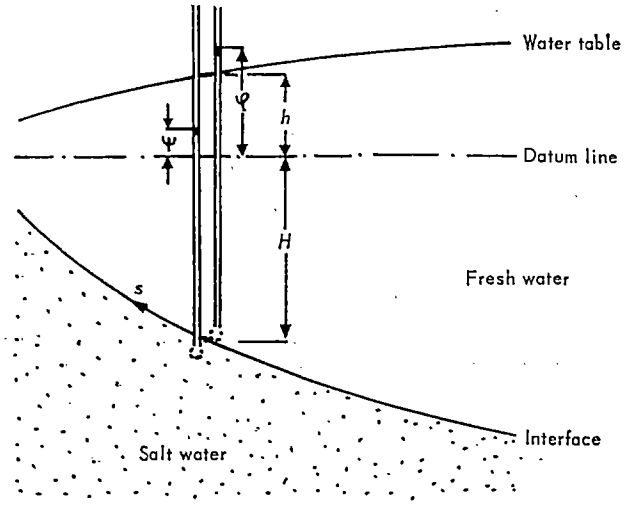


FIG. 5. Flow of fresh and salt water.

In deltas numerous river branches cut up the land into strips, bounded at both sides by open water. Near the sea these rivers carry salt water, while below the strip of land salt ground water will be present when the unconfined aquifer has an unlimited depth (Fig. 6). Assuming equal levels of the bounding estuaries and thus salt water at rest, to the neglect of vertical flow components, the shape of the fresh-water pocket may be calculated as follows:

Darcy $\quad q = -k\,(h + H) \cdot \frac{dh}{dx}$;

Continuity $\quad \frac{dq}{dx} = P$;

Ghyben-Herzberg $\quad h = \Delta \cdot H$;

in which q is the flow per unit width, k the coefficient of permeability of the unconfined aquifer and P the amount of available rainfall percolating downward to the ground-water supply. Integration of the continuity equation yields $q = P.x + C_1$ with the integration constant according to the boundary condition $x = 0$, $q = 0$ equal to zero. This value of q and the value of h of the Ghyben-Herzberg relationship substituted in Darcy's equation gives after rearranging terms

$$H \cdot dH = -\frac{P \cdot x}{(1 + \Delta) \cdot \Delta \cdot k} \cdot dx.$$

Integrated between the limits $x = x$, $H = H$ and $x = L$, $H = 0$

$$H^2 = \frac{P \cdot (L^2 - x^2)}{(1 + \Delta) \cdot \Delta \cdot k}.$$

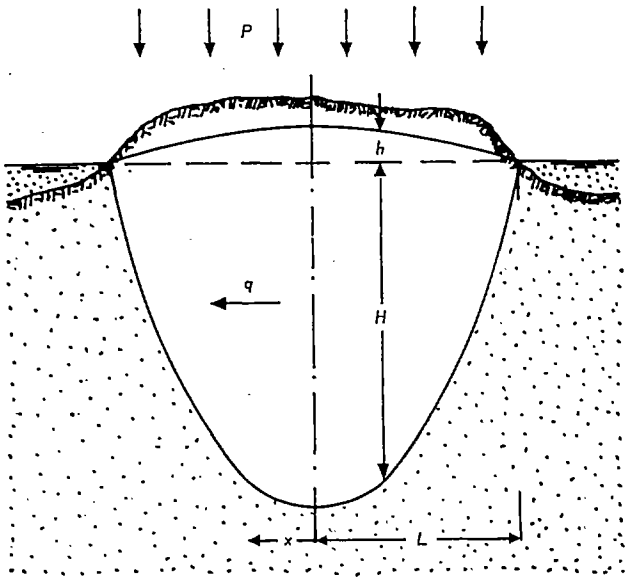


FIG. 6. Freshwater pocket in an unconfined aquifer of unlimited depth.

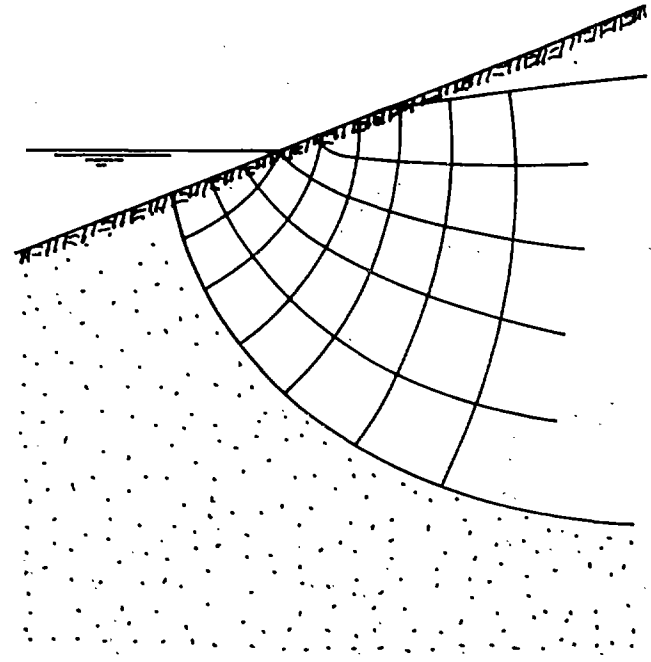


FIG. 7. Actual shape of freshwater pocket near shoreline.

With for instance $L = 5{,}000$ metres, $P = 500$ mm./year $= 0.00137$ metre/day, $\Delta = 0.02$ and $k = 50$ metre/day, the maximum depth of the fresh-water pocket floating upon the underlying salt water becomes 183 metres (at $x = 0$) and here the ground-water table is 3.66 metres above the level of the bounding stream.

In the centre of the strip of land vertical flow components may indeed be neglected and here the calculation given above yields correct results. Near the shoreline however, flow and equipotential lines are curved, $\varphi \neq h$ and the fresh-water depth is larger as indicated by the formula above to form a seepage face for fresh-water outflows (Fig. 7). With a flow net analysis this depth can easily be calculated. For the example mentioned above a depth of about 5 metres would have been found, having only a negligible influence on the shape of the fresh-water pocket.

With unconfined aquifers of shallow depth, the penetration of sea-water is limited. Over the length A of the intruded sea-water wedge (Fig. 8), the shape of the fresh-salt water interface remains the same as without the presence of an impervious base, giving for this length the relation

$$(L - A)^2 = L^2 - \frac{(1 + \Delta) \cdot \Delta \cdot k \cdot H_0^2}{P}$$

or with A small, by approximation

$$A = \frac{(1 + \Delta) \cdot \Delta \cdot k \cdot H_0^2}{2\,PL}$$

in which H_0 is the depth of the aquifer below the level of the bounding streams. For the same example as mentioned above and with $H_0 = 50$ metres, the penetration A becomes 190 metres only. Landward of this sea-water wedge the flow of ground water is not influenced by the presence of salt water. The impervious base impedes outflow and for the example mentioned above the water table in the centre of the strip of land rises to 6.88 metres above the level of the bounding streams.

When ground water is abstracted evenly over the entire area of an unconfined aquifer, its influence can be taken into account as an even reduction of the amount of available rainfall. An abstraction of, for instance, 70 per cent of this rainfall leaves 30 per cent to percolate downward to recharge the ground-water supply. With unconfined aquifers of unlimited thickness, freshwater depths and freshwater levels are thus reduced to $\sqrt{0.3}$ or 55 per cent of their original values. With shallow aquifers and a small penetration of salt water, the length of the intruded sea-water wedge increases a little more than inverse proportional and freshwater depths decrease a little less than proportional to the reduction in the amount of available rainfall. When in the example mentioned above the amount of available rainfall is reduced to 30 per cent, the length of the intruded sea-water wedge increases to 664 metres, that is by a factor $3.5 = \frac{1}{0.29}$. The freshwater depth in the centre of the strip of land drops to 2.50 metres above the level of the bounding stream, that is by a factor 0.36.

With the same amount of abstraction, the lowering of the water table could be reduced by concentrating the artificial abstraction as near as possible to the point of natural discharge into the bounding stream. With unconfined aquifers of unlimited depth any concentration of the abstraction, however, increases the danger of brackish water coning. A point abstraction drawing the water table locally below the level of the bounding stream even results in the upconing of salt water (Fig. 9). In this respect shallow aquifers are in a more favourable position. Provided that seaward of the abstraction a freshwater ridge down to the impervious

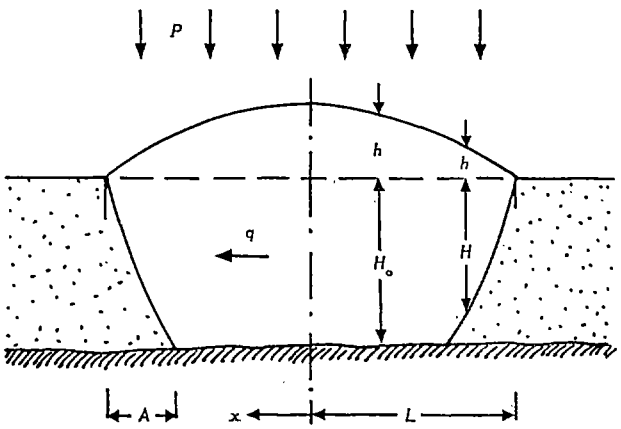


FIG. 8. Freshwater pocket in a shallow aquifer.

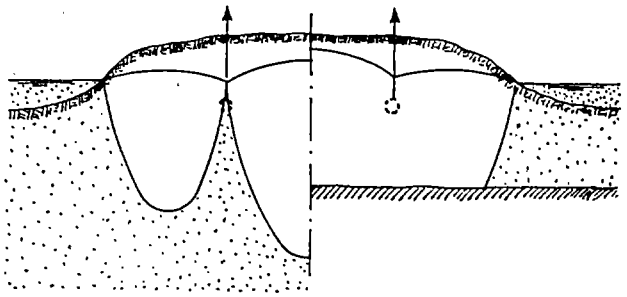


FIG. 9. Point abstraction of fresh water in deep and shallow aquifers.

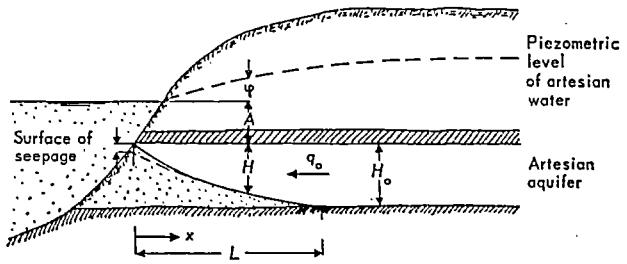


FIG. 10. Penetration of salt water in an artesian aquifer.

base is maintained, upconing of salt or brackish water is impossible.

With artesian aquifers confined at top and bottom by fully impervious layers, penetration of salt water is only possible when direct contact with the bounding stream is present as shown in Figure 10. With the notations of this figure, the shape of the salt-water wedge can be calculated with

Darcy $\quad q_0 = kH \cdot \frac{d\varphi}{dx};$

Continuity $\quad q_0 = \text{constant};$

Ghyben-Herzberg $\quad \varphi = (A + H) \cdot \Delta;$

in which k is the coefficient of permeability of the confined aquifer. Elimination of φ gives

$$H \cdot dH = \frac{q_0}{\Delta \cdot k} \cdot dx$$

integrated between the limits $x = 0, H = 0$ and $x = x$, $H = H$

$$H^2 = \frac{2\,q_0}{\Delta \cdot k} \cdot x \quad \text{or} \quad H = \sqrt{\frac{2\,q_0}{\Delta \cdot k}} \cdot x$$

and

$$\varphi = \Delta \cdot A + \sqrt{\frac{2\,q_0}{k} \cdot \Delta \cdot x}.$$

The length L of the salt-water wedge is given by

$$L = \frac{\Delta \cdot k \cdot H_0^2}{2\,q_0}.$$

Freshwater abstractions farther inland should leave a sufficient amount q_0 to be wasted to the bounding stream, so as to keep the length L of the salt-water wedge within reasonable limits.

With leaky artesian aquifers, situated above an impervious base and overlain by a less-pervious layer with a resistance c against vertical water movement, salt-water penetration is also possible when direct contact with the bounding stream is absent. With the help of Figure 11 the shape of the freshwater tongue seaward of the shoreline may be calculated with

Darcy $\quad q = -ky \cdot \frac{d\varphi}{dx} \qquad (1)$

Continuity $\quad \frac{dq}{dx} = \frac{\Delta \cdot A - \varphi}{c} \qquad (2)$

Ghyben-Herzberg $\quad \varphi = \Delta\,(A + y) \qquad (3)$

Multiplying the corresponding parts of equations (1) and (2) gives

$$q \cdot dq = -\frac{k}{c}(\Delta \cdot A - \varphi) \cdot y \cdot d\varphi$$

or with φ from (3)

$$q \cdot dq = \Delta^2 \cdot \frac{k}{c} \cdot y^2 \cdot dy$$

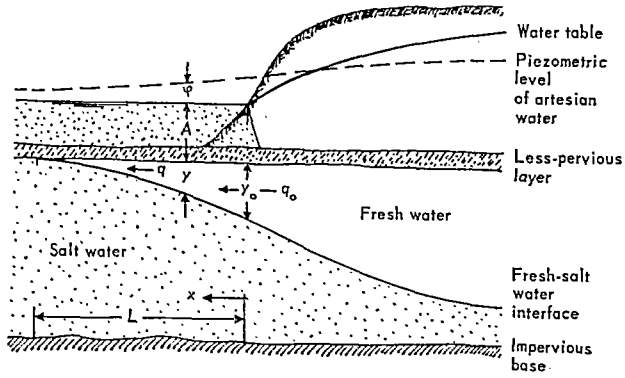


FIG. 11. Freshwater tongue below semi-pervious layer.

which integrated yields

$$q^2 = \frac{2}{3}\,\Delta^2\,\frac{k}{c}\,y^3 + C \qquad (4)$$

with the integration constant C from the boundary condition $x = L$, $q = 0$, $y = 0$ equal to zero.

Substituting the value of q from (4) and the value of φ from (3) in (1) gives

$$\sqrt{\frac{2}{3}\,\Delta^2\,\frac{k}{c}\,y^3} = -\,\Delta\,ky\,\frac{dy}{dx} \quad \text{or} \quad dx = -\sqrt{\frac{3}{2}\,kc} \cdot \frac{dy}{\sqrt{y}}.$$

Integration between the limits $x = 0$, $y = y_0$ and $x = L$, $y = 0$ gives

$$L = \sqrt{6\,kc} \cdot \sqrt{y_0} = \sqrt[3]{\frac{18\,kc^2}{\Delta} \cdot q_0}. \qquad (5)$$

For great lengths freshwater tongues stretch below the bottom of the sea. With for instance $k = 50$ metres/day, $c = 2{,}000$ days, $\Delta = 0.02$ and the outflow of artesian water at the shoreline q_0 equal to 0.5 cu. metres/metre/day, the length of the freshwater tongue is no less than 4.5 kilometres, while the freshwater depth at the shoreline y_0 equals 33.5 metres. Again ground-water abstractions farther inland should leave sufficient fresh water to be wasted to the sea so as to keep this depth above the minimum value considered necessary.

Landward of the shoreline, the artesian flow of fresh water also depends on the conditions in the unconfined aquifer above the semi-pervious layer. Calculation of the shape of the freshwater pocket here can best be carried out by trial and error (D. K. Tedd and L. Huisman, "Ground-water Flow in the Netherlands Coastal Dunes", *Journal of the Hydraulics Division*, Proceedings of the American Society of Civil Engineers, July 1959). When the artesian aquifer has a limited depth only, the fresh-salt water interface will intersect the impervious base and the calculations given above only apply seaward of this point of intersection. Landward of this point, the freshwater depth is constant, equal to the thickness of the artesian aquifer, simplifying calculations and raising the piezometric level of the fresh water.

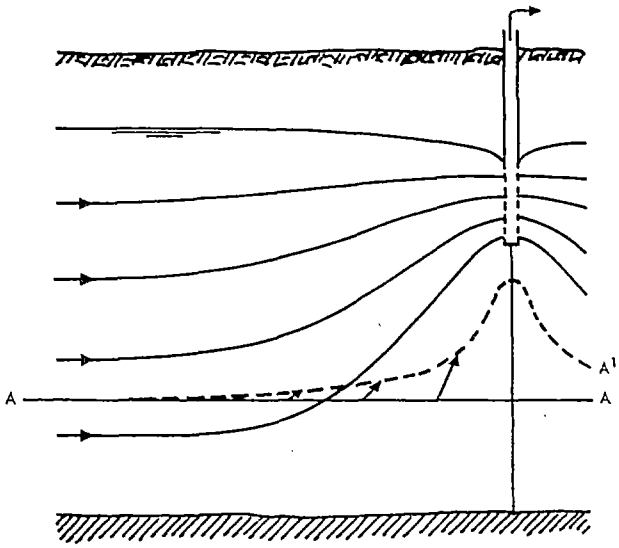


FIG. 12. Salt water coning.

SALT AND BRACKISH WATER CONING

Ground-water abstraction with a partly penetrating well will result in a flow of ground water to the well screen from all directions. In the immediate vicinity of such a well, the flow lines are curved and next to horizontal components of flow, strong vertical flow components are present. Now when the aquifer carries salt water up to the fully drawn line AA in Figure 12, these vertical flow components will result in a drawing up of the fresh-salt water interface. Ignoring all differences in physical characteristics between fresh and salt water, after a certain amount of abstraction the fresh-salt water interface will follow the dotted line of Figure 12 and the cone of salt water will grow in height and lateral extent as abstraction continues. However, salt water has a specific gravity 2 to 2.5 per cent higher than fresh water and as soon as a vertical displacement of the interface occurs, a second flow pattern sets in, the sagging out of the salt-water cone by gravity. When abstraction continues indefinitely, a stationary interface will result, the height of the salt water cone being a function of the rate of point abstraction. Apart from a general rise of the fresh-salt water interface (see last section), the difference in specific gravity between fresh and salt water is so large that salt water cones attain a height of only a few metres. With properly constructed wells, they will never endanger the quality of the water abstracted.

The transition from fresh to salt water is not an abrupt one, but between the two types of water a diffusion zone is present in which the chloride content increases gradually with depth (Fig. 13). The upper part of this diffusion zone carries brackish water with a low chloride content and consequently an only slightly larger specific gravity. A brackish water with a chloride content of for instance 800 p.p.m. has a specific gravity 0.1 per cent higher than that of fresh water. The drawing up of this brackish water by vertical flow components occurs in exactly the same way as described above. The sagging out by the higher specific gravity, however, is decreased by a factor of 20 to 25 and brackish water cones may thus attain considerable dimensions, even reaching the lower part of the well screen (Fig. 14) and raising the chloride content of the ground water abstracted. Although from a physical point of view there is

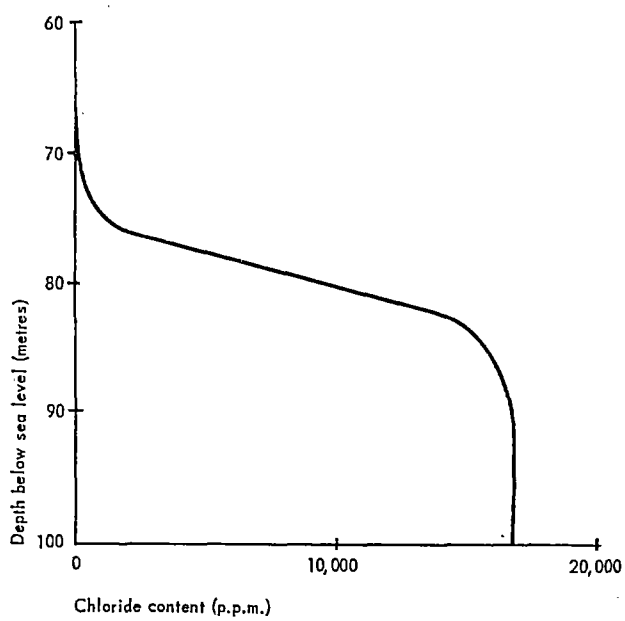


FIG. 13. Diffusion zones between fresh and salt water (dune water catchment area of Amsterdam).

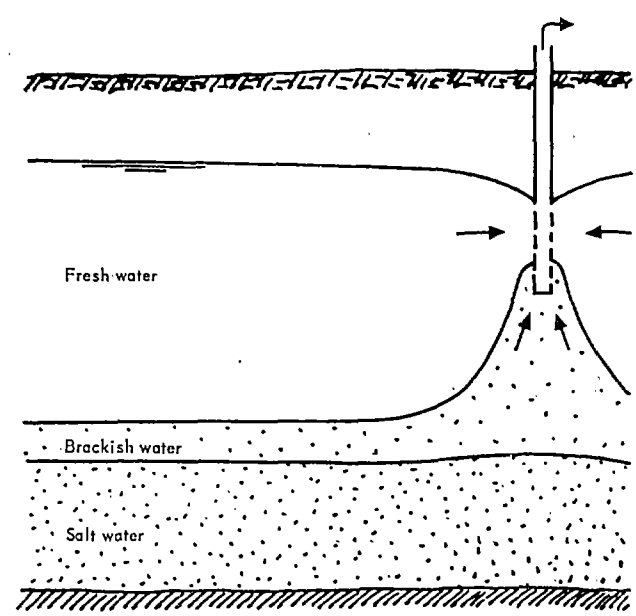


FIG. 14. Brackish water coning.

little difference between fresh water and brackish water with 800 p.p.m. chlorides, from the consumer's point of view the latter is salt water, unfit for human consumption, agriculture and many other purposes.

The best way to prevent upconing of brackish water is by spreading the abstraction as much as possible, using systems of small capacity wells or even galleries instead of one or a few wells pumped at excessive rates. This may endanger the economy of the project for ground-water abstraction and in some cases a cheaper solution may be obtained by concentrating the abstraction in those areas where between the bottom of the well and the fresh-salt water interface a less-pervious layer is present. Even when this layer has only a small resistance or has holes and openings, it will still distribute point abstractions over a larger territory, reducing vertical components of flow. When in a homogeneous aquifer brackish water coning cannot be prevented, a good quality of water abstracted may be maintained by pumping each well for a limited period only. Drawing up of brackish water cones requires time and when abstraction is shifted to other wells the moment these cones reach the bottom of the screen, an increase of the chloride content of the water recovered will not occur. Left alone, the brackish water cone will sag out by gravity and will move away from the well in the direction of the general ground-water flow. After a period of rest, one year for instance, such a well is again able to produce fresh water. After brackish water cones have been drawn up, they will surround the lower part of the screen only. Over the upper part of the screen the inflow of ground water is still fresh and by abstracting this water separately (Fig. 15a), a rise in chloride content can be prevented. With regard to the danger of short-circuiting, the separate screens of Figure 15b) will give better results. In both cases, however, rather large amounts of brackish water have to be abstracted to keep the chloride content of the fresh water down. Basic costs of construction as well as running costs are thus appreciably higher, while disposal of the brackish water recovered is often a problem difficult to solve.

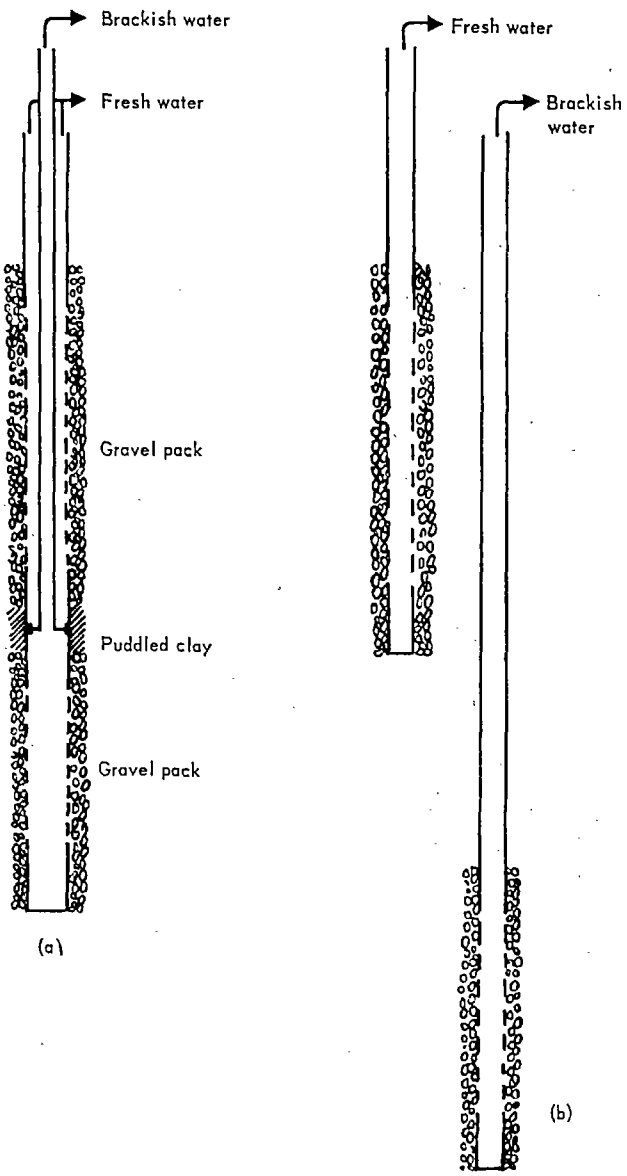


FIG. 15. Separate recovery of fresh and brackish water.

Résumé

Les eaux souterraines dans les deltas (L. Huisman)

L'eau de l'atmosphère et les eaux superficielles des cours d'eau et des lacs traversent la surface du sol et la zone d'aération, jusqu'à ce qu'elles atteignent la nappe souterraine et s'accumulent dans la zone de saturation. Les eaux souterraines ainsi formées ne sont pas stagnantes, mais s'écoulent à travers le sol dans le sens de la pente générale de la nappe souterraine. Tôt ou tard, les eaux souterraines reparaissent à la surface, sous forme de sources visibles, ou sous forme d'écoulements souterrains invisibles dans des cours d'eau et des lacs (cycle des eaux souterraines). Les rivières se jettent dans les fleuves qui amènent l'eau à la mer, d'où l'eau retourne dans l'atmosphère par évaporation (cycle hydrologique).

Du point de vue qualitatif, les eaux souterraines se comportent dans les deltas exactement de la même

façon que dans toute autre région du globe. De même, dans les deltas, la formation, l'écoulement et le débit des eaux souterraines obéissent aux lois hydrologiques générales; mais du point de vue quantitatif, on constate de nombreuses différences dont les plus importantes sont les suivantes :

1. Les deltas sont constitués par des dépôts sédimentaires non consolidés, d'une grande porosité, couverts d'un réseau serré de bras et de ramifications. De ce fait, les eaux souterraines sont en contact plus étroit avec les eaux de surface qui s'écoulent dans le fleuve et ses bras. Le niveau et l'écoulement des eaux souterraines dépendent donc pour une large part des conditions auxquelles sont soumises les eaux superficielles.

2. Les dépôts sédimentaires non consolidés des deltas ont en général une forte teneur en eau et un coefficient de transmissivité élevé. Étant donné, en outre, la brièveté du parcours, l'approvisionnement en eaux souterraines dans les deltas est abondant et ces eaux peuvent être utilisées très largement à diverses fins. Les conditions sont aussi favorables à une recharge artificielle — ce qui permet d'éviter facilement un abaissement excessif de la nappe souterraine par suite de prélèvements importants.

3. Le niveau de la surface du sol dans les deltas marque peu de variations et n'est pas d'ordinaire beaucoup plus élevé que celui du fleuve. Dans les deltas des régions tropicales humides, le volume des précipitations varie considérablement de la saison sèche à la saison des pluies. Sans intervention artificielle, il se produira des inondations à la saison des pluies, alors que, pendant la saison sèche, les nappes d'eaux souterraines se trouvent à une telle profondeur au-dessous du niveau du sol qu'elles présentent peu d'utilité pour l'agriculture.

4. Lorsque les marées entraînent des fluctuations dans le niveau du fleuve et de ses bras, le niveau de la nappe souterraine des deltas marque des variations correspondantes. Les variations de niveau dues aux marées se propagent à de grandes distances dans les nappes artésiennes, tandis que leur propagation est pratiquement négligeable dans les nappes libres.

5. Dans les nappes côtières souterraines, la couche d'eau douce flotte au-dessus de la couche d'eau salée — ces deux couches superposées étant séparées par une ligne de démarcation assez nette. La profondeur à laquelle se trouve cette interface dépend de l'écart entre les niveaux piézométriques respectifs des deux couches. Si l'on prélève de l'eau douce, cet écart diminue et l'interface s'élève, mettant ainsi en danger la qualité de l'eau récupérée. On peut calculer la position résultante de l'interface dans diverses conditions géohydrologiques, et établir la forme des «coins» (*wedges*) d'eau salée et celle des «langues» (*tongues*) d'eau douce.

6. Dans les nappes souterraines côtières, il y a entre la couche d'eau douce et la couche d'eau salée une zone de diffusion où se trouvent des eaux saumâtres. Dans la partie supérieure de cette zone, la teneur en sel est encore si faible qu'en fait cette eau est de l'eau douce. Si l'on procède à un prélèvement ponctuel dans une nappe homogène, cette eau saumâtre est aspirée dans le puits, ce qui rend l'eau récupérée impropre à la plupart des usages. On peut empêcher la remontée de l'eau saumâtre par divers procédés, ou encore prélever séparément cette eau saumâtre, ce qui permet de maintenir à un faible taux la teneur en sel de l'eau douce.

La concentration chimique par évaporation des eaux souterraines dans les deltas

Marc Schoeller

Par suite de leur faible altitude au-dessus du niveau de la mer, les alluvions des deltas renferment très souvent une nappe d'eau à faible profondeur sous le sol. Cette nappe d'eau de l'amont à l'aval se rapproche de plus en plus de la surface.

Il s'ensuit qu'une évapotranspiration se fait aux dépens de la nappe, d'où une concentration de sels dissous. Cette concentration est accentuée dans le sens de l'écoulement de la nappe.

Il faut donc nous attendre à une salure des eaux de la nappe dans les deltas, salure d'autant plus importante que l'on s'approche de la mer. Cette salure peut d'ailleurs aussi intéresser le sol par suite des remontées capillaires d'eau.

Nous exposons ici les lois qui gouvernent cet accroissement de la salure.

Il est évident que l'influence de l'évapotranspiration est différente suivant que la nappe est à faible ou à grande profondeur : lorsque la nappe est à grande profondeur, l'évapotranspiration n'agit que sur l'eau de la zone d'infiltration qu'elle concentre plus ou moins. Et c'est cette eau concentrée qui arrive à la nappe.

Dans le cas contraire, l'évapotranspiration agit directement sur l'eau de la nappe et les phénomènes de concentration sont beaucoup plus intenses. La concentration augmente alors très nettement de l'amont à l'aval. Nous allons établir un certain nombre d'équations reliant la concentration et l'évapotranspiration; elles nous permettront de calculer la perméabilité : c'est là leur importance.

Lorsque la surface d'une nappe libre se trouve à faible profondeur, il se produit une évaporation de l'eau de la nappe. Le taux de cette évaporation dépend à la fois de la profondeur à laquelle se trouve la surface de la nappe, de la nature pétrographique, de la hauteur de la frange capillaire, de la densité de la végétation, de la profondeur à laquelle les racines descendent; quant à la profondeur à partir de laquelle l'eau se concentre, elle y varie suivant qu'il y a simple évaporation d'un sol nu, ou évapotranspiration par la végétation. Dans le second cas, elle est plus grande. Cette profondeur dépend également de la nature du sol : l'évaporation d'un sol à grain fin peut se faire beaucoup plus profondément que celle d'un sol à gros grain, surtout si celui-ci est meuble. Ainsi, suivant les conditions du sol et de la végétation, la profondeur jusqu'à laquelle une évaporation notable peut se produire varie de 2 à 5 mètres. Au-delà, le taux d'évaporation est relativement faible. D'après Loukachev (1958), l'évaporation cesse pratiquement à une profondeur de 14 cm en Sibérie occidentale et de 278 à 300 cm en Asie moyenne.

Nous pouvons essayer de nous rendre compte de l'évolution de la concentration dans une nappe qui s'écoule, et qui subit une évapotranspiration constante le long du parcours envisagé.

Soit une nappe (fig. 1) ayant un débit de q_0 à son origine, où l'épaisseur de la nappe est H. Le front de la nappe a une longueur F. La nappe évapore par mètre carré et par seconde la hauteur d'eau e, et la nappe gagne par mètre carré et par seconde une hauteur d'eau p, provenant de l'infiltration de l'eau de pluie.

On admettra que la pluie n'apporte qu'une dilution de l'eau d'infiltration ou plutôt qu'elle ne fait que diminuer le taux d'évapotranspiration lorsque $e - p > 0$, ce qui a lieu le plus généralement.

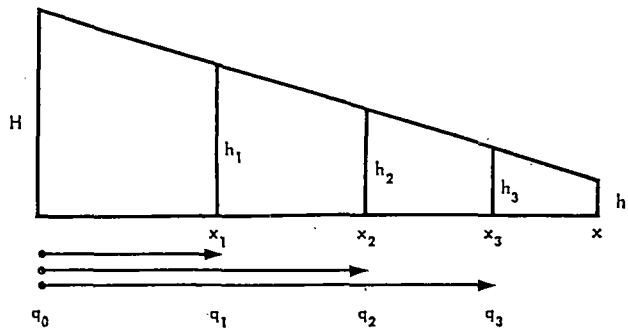


FIG. 1. Nappe d'eau évaporée par sa surface.

On a donc en x la variation du débit :

$$dq = -(e-p)\mathrm{F}\,dx \qquad (1)$$

d'où

$$q = q_0 - (e-p)\mathrm{F}x \text{ en } x \qquad (1')$$

D'autre part, en appliquant la loi de Darcy, en x

$$q = -\mathrm{K}h\mathrm{F}\frac{dh}{dx} \qquad (2)$$

h étant l'épaisseur de la nappe en x
(1) et (2) donnent :

$$q\,dq = \mathrm{K}(e-p)\,\mathrm{F}^2 h\,dh$$

Par intégration, cette dernière équation devient :

$$q^2 = q_0^2 - \mathrm{K}(e-p)\,\mathrm{F}^2(\mathrm{H}^2 - h^2) \qquad (3)$$

(1) et (3) donnent :

$$(e-p)x^2 - 2q_0\frac{x}{\mathrm{F}} + \mathrm{K}(\mathrm{H}^2 - h^2) = 0 \qquad (4)$$

Du fait de l'évapotranspiration, la concentration augmente de l'amont à l'aval pouvu que $e - p > 0$.

Soit C_0 la concentration de l'eau de la nappe à l'origine et C_1, C_2, C_3... les concentrations en x_1, x_2, x_3... Il est évident que l'on a la relation :

$$\mathrm{C}_0 q_0 = \mathrm{C}_1 q_1 = \mathrm{C}_2 q_2 = \mathrm{C}_3 q_3 = \cdots = b \qquad (5)$$

Comme b est constant tout au long de la nappe, on a :

$$\mathrm{C} = \frac{b}{q_0 - (e-p)\mathrm{F}x} \qquad (6)$$

Cette relation n'est valable que lorsqu'il s'agit de la concentration du chlore de l'eau. La concentration des autres éléments peut, en effet, subir des perturbations. Les cations Ca^{++}, Mg^{++}, Na^{+}, K^{+} peuvent être affectés par des échanges de bases au cours de leur trajet; SO_4 peut subir une réduction; HCO_3 a tendance à rester constant, car il est déjà à l'état de saturation. Au cours de la concentration, il peut y avoir des saturations : saturation de $CaCO_3$, de $CASO_4$, etc. La concentration de tel ou tel de ces éléments n'est donc pas proportionnelle à l'évaporation; il en est de même de la concentration totale. *Seule la concentration en chlore, qui ne subit ni échange de bases, ni précipitation, est proportionnelle à l'évaporation.*

De l'équation (6), on tire les valeurs des distances x_1 et x_2 où les concentrations de l'eau de la nappe sont C_1 et C_2

$$x_1 = \frac{q_0}{(e-p)\mathrm{F}}(1 - \mathrm{C}_0/\mathrm{C}_1) \qquad (7)$$

$$x_2 = \frac{q_0}{(e-p)\mathrm{F}}(1 - \mathrm{C}_0/\mathrm{C}_2 \qquad (7')$$

Et par conséquent, l'on a aussi :

$$\mathrm{C}_2 = \frac{x_1\mathrm{C}_0}{x_1 + x_2(\mathrm{C}_0/\mathrm{C}_1 - 1)} \qquad (8)$$

$$x_2 = x_1\frac{\mathrm{C}_1}{\mathrm{C}_2} \times \frac{\mathrm{C}_2 - \mathrm{C}_0}{\mathrm{C}_1 - \mathrm{C}_0} \qquad (9)$$

$$x_3 - x_1 = (x_2 - x_1)\frac{\mathrm{C}_2}{\mathrm{C}_3} \times \frac{\mathrm{C}_3 - \mathrm{C}_1}{\mathrm{C}_2 - \mathrm{C}_1} \qquad (9')$$

La distance X à laquelle toute l'eau de la nappe se trouve évaporée se tire de l'équation (1)

$$\mathrm{X} = \frac{q_0}{(e-p)\mathrm{F}}. \qquad (10)$$

CALCUL DE L'ÉVAPOTRANSPIRATION

L'évapotranspiration $(e - p)$ peut être calculée à partir des équations (6) ou (10) qui donnent :

$$e - p = \frac{q_0 - b/\mathrm{C}}{\mathrm{F}x} \qquad (11)$$

$$e - p = \frac{q_0}{\mathrm{F}\mathrm{X}} \qquad (11')$$

CALCUL DE LA PERMÉABILITÉ

On pourrait théoriquement calculer la perméabilité du terrain aquifère en connaissant les variations de concentration suivant x_1, x_2, etc.
L'équation (4) donne en effet :

$$\mathrm{K} = \frac{2q_0 x/\mathrm{F} - (e-p)\,x^2}{(\mathrm{H}^2 - h^2)} \qquad (12)$$

En introduisant $(e - p)$ de l'équation (11), on obtient :

$$\mathrm{K} = \frac{x(q_0 + b/\mathrm{C})}{\mathrm{F}(\mathrm{H}^2 - h^2)} = \frac{xq_0\,(1 + \mathrm{C}_0/\mathrm{C})}{\mathrm{F}\,(\mathrm{H}^2 - h^2)} \qquad (13)$$

Si l'on prend la concentration $\mathrm{C}x$ à X, on a :

$$\mathrm{K} = \frac{\mathrm{X}q_0(1 + \mathrm{C}_0/\mathrm{C}_x)}{\mathrm{F}(\mathrm{H}^2 - h^2)} \qquad (14)$$

Or C_x est voisin de 5 000 à 6 000 rCl.
Et si $h \simeq 0$

$$\mathrm{K} = \frac{\mathrm{X}q_0\,(1 + \mathrm{C}_0/\mathrm{C}_x)}{\mathrm{F}\mathrm{H}^2} \qquad (15)$$

A la distance $\mathrm{X}_c = \infty$, toute l'eau est évaporée. Mais cette concentration maximale, à partir de laquelle se fait la précipitation, a lieu en réalité à une distance X_{cm}. Pour le chlore, la concentration $\mathrm{C}_{xm} = 6\,000$ rCl environ. Au-delà de cette distance, C_m ne varie pas, et à X_{cm} on n'a pas $q = 0$, mais :

$$q_{xm} = \frac{\mathrm{C}_0}{6\,000\,r\,\mathrm{Cl}}. \qquad (16)$$

Pour la distance X_{cm}, on a aussi :

$$\mathrm{X}_{cm} = x_1\frac{\mathrm{C}_1}{\mathrm{C}_{xm}} \times \frac{\mathrm{C}_{xm} - \mathrm{C}_0}{\mathrm{C}_1 - \mathrm{C}_0} = x_1\frac{\mathrm{C}_1}{6\,000} \times \frac{6\,000 - \mathrm{C}_0}{\mathrm{C}_1 - \mathrm{C}_0} \qquad (17)$$

Pratiquement $\mathrm{X}_c = \infty$; $\mathrm{X}_c = 6\,000$

Reprenons l'équation (14). Remplaçons C_x par C_{xm} et X par la valeur X_{cm} de l'équation (16); h devient

alors négligeable devant H, et C_0 négligeable devant C_{xm}, on obtient alors :

$$K = \frac{q_0 x_1}{FH^2} \times \frac{C_1}{C_1 - C_0} \qquad (18)$$

INFLUENCE DE LA VITESSE DE CIRCULATION DE L'EAU SUR LA COURBE DE CONCENTRATION

La vitesse de circulation influence la forme de la courbe normale de concentration $C = f(t)$.

Si à partir d'un point x_1 la vitesse de circulation de l'eau augmente, la courbe sera moins concave. Si, au contraire, la vitesse de circulation diminue, la concavité s'accentuera (fig. 2).

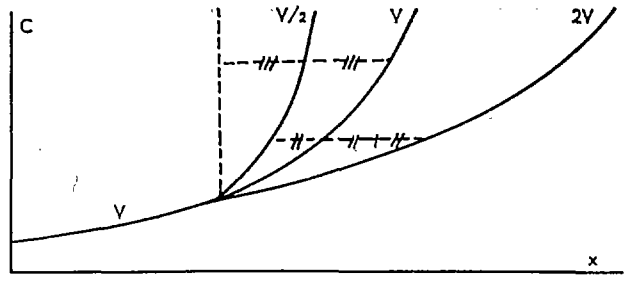


FIG. 2. Influence de la vitesse de circulation sur la concentration des sels de l'eau de la nappe.

INFLUENCE DE L'INTENSITÉ DE L'ÉVAPOTRANSPIRATION SUR LA COURBE DE CONCENTRATION

L'évapotranspiration dépend de la densité et de la nature de la végétation aussi bien que de la nature du sol et de son épaisseur au-dessus de la surface de la nappe; tout cela peut varier de l'amont à l'aval d'une nappe.

Vers l'aval des nappes des alluvions quaternaires, la surface piézométrique se rapproche de la surface du sol, les terrains deviennent de plus en plus argileux avec des franges capillaires de plus en plus hautes. De ce fait, l'évaporation et l'évapotranspiration deviennent plus grandes. Cependant, on peut rencontrer vers l'aval des zones où des hauteurs plus grandes de terrain surmontent la nappe et où l'évapotranspiration est moins intense.

Une augmentation du taux d'évaporation aura un effet semblable à celui d'une diminution de la vitesse de circulation de l'eau; inversement, une diminution du taux d'évapotranspiration aura un effet semblable à celui d'une augmentation de la vitesse de circulation (fig. 3).

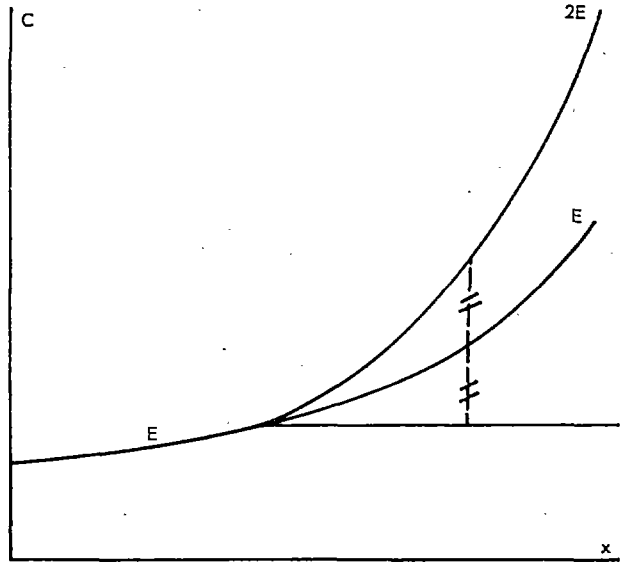


FIG. 3. Influence de l'intensité de l'évapotranspiration sur la concentration des sels de l'eau de la nappe.

La différence dans la construction des deux types de courbe vient du fait que, dans le premier cas, on reporte les points à droite ou à gauche de la courbe normale, tandis que, dans le second cas, on reporte les points en haut ou en bas de la courbe normale. Le plus souvent, les deltas vont en s'élargissant vers l'aval, là où la nappe se rapproche de la surface du sol. Nous avons donc à envisager le cas de nappes divergentes (fig. 4). On a (S étant la surface de l'impluvium) :

$$q = q_0 - (e - p)S \qquad (1)$$

Or (ω étant l'angle mesuré en radians)

$$S = \frac{\omega}{2}(X^2 - x_0^2) \qquad (2)$$

On a donc :

$$q = q_0 - (e - p)\frac{\omega}{2}(X^2 - x_0^2) \qquad (3)$$

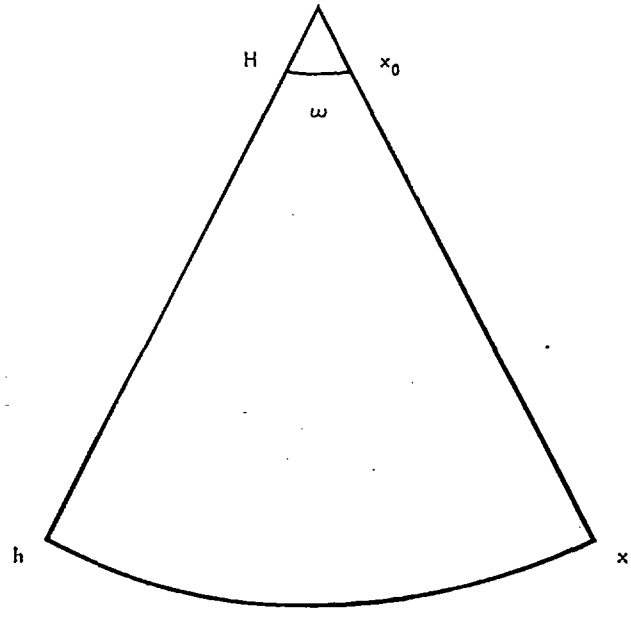


FIG. 4. Nappe divergente.

Or (Z étant la hauteur de la nappe à X)

$$q = -\,K\omega\frac{x}{dx}Z\,dZ \qquad (4)$$

On a donc :

$$-\,K\,\omega\,Z\,dZ = q^0\frac{dx}{x} = \frac{(e-p)}{2}\omega x\,dx + (e-p)\frac{\omega}{2}x_0^2 + \frac{dx}{x} \qquad (5)$$

qui intégrée donne :

$$-\frac{1}{2}K\omega Z^2 = \left[q_0 + (e-p)\frac{\omega}{2}x_0^2\right]\log_e x - (e-p)\frac{\omega}{2}\frac{1}{2}x^2 + \text{Const.} \qquad (6)$$

Si à $x = X$, $Z = h$, et à $x = x_0$, $Z = H$, on a :

$$-\frac{1}{2}K\omega(H^2 - h^2) = \left[q_0 + (e-p)\frac{\omega}{2}x_0^2\right]\log_e\frac{X}{x_0} - (e-p)\frac{\omega}{4}(X^2 - x_0^2) \qquad (7)$$

En associant les équations (3) et (7), on obtient :

$$q = \frac{K\omega(H^2 - h^2) + (e-p)\frac{\omega}{2}(X^2 - x_0^2)}{2\log_e X/x_0} - (e-p)\frac{\omega}{2}X^2 \qquad (8)$$

Comme :

$$Cq = C_0q_0 = C_1q_1 = \cdots = b \qquad (9)$$

on a donc avec l'équation (3)

$$(e-p) = \frac{2q_0}{\omega(x^2 - x_0^2)}(1 - C_0/C) \qquad (10)$$

ou

$$C = \frac{q_0C_0}{q_0 - (e-p)\,\omega(x^2 - x_0^2)/2} \qquad (10')$$

Et l'on a par conséquent aussi :

$$C_2 = \frac{C_0}{1 - \left(1 - \frac{C_0}{C_1}\right)\left(\frac{x_2^2 - x_0^2}{x_1^2 - x_0^2}\right)}$$

En résumé, dans une nappe libre qui s'évapore par sa surface, nous avons établi l'existence de relations qui s'expriment mathématiquement entre la teneur en chlore, le taux d'évaporation, la distance parcourue, la vitesse et tout particulièrement la perméabilité.

L'augmentation de la concentration des eaux souterraines dans les deltas doit amener une évolution de la composition chimique vers l'aval [1]. Au fur et à mesure que la concentration s'accroît, le sels les moins solubles précipitent quand leur produit de solubilité est atteint; c'est le cas des sulfates, du calcium, du magnésium; au contraire les chlorures et le sodium beaucoup plus solubles voient leur concentration augmenter d'amont en aval. Les rapports des éléments chimiques entre eux sont donc modifiés, même dans le cas des bicarbonates dont les concentrations restent relativement constantes à cause de la tension du CO_2 du sol.

Dans ces conditions, si, en amont, il y a une eau bicarbonatée présentant une séquence $rCO_3H > rSO_4 > rCl$ pour les anions, et $rCa > rMg > rNa$ pour les cations, on passera progressivement à l'aval à une séquence $rCl > rSO_4 > rHCO_4$ pour les anions et $rNa > rMg > rCa$ pour les cations, en passant par tous les types intermédiaires :

$rSO_4 > r\,HCO_3 > rCl$
$rSO_4 > rCl > rHCO_3$
$rCl > rSO_4 > rCO_3$
et $rCa > rNa > rMg$
$rNa > rCa > rMg$
$rNa > rMg > rCa$

1. Les modifications de la composition chimique par concentration ont été exposées par Henri Schoeller (1934, 1956, 1962).

Summary

Chemical concentration by evaporation in underground waters in deltas (Marc Schoeller)

Because of their low altitude above sea level, alluvial deposits in deltas very often contain ground water at a short distance below the soil. As the ground water flows in a downstream direction it comes nearer and nearer to the surface.

As a result, evapotranspiration takes place at the expense of the ground water and a concentration of dissolved salts ensues. This concentration increases in the direction in which the ground water flows.

We must therefore expect salinity in deltaic ground water, increasing with proximity to the sea. This salinity may also affect the soil as a result of the capillary movement of water.

The salt content varies in the downstream direction according to the solubility product. The total concentration increases, but the relations of the contents are modified.

This paper deals with the laws that govern this increase in salinity.

Discussion

VOLKER estime que le phénomène décrit de façon aussi nette et claire par M. Schoeller est un des facteurs qui conditionnent la teneur en sel des eaux souterraines dans les deltas. Dans beaucoup de cas, ce phénomène est la cause principale, notamment dans les deltas des régions semi-arides et arides où les gradients sont généralement forts et où l'évaporation dépasse de beaucoup la pluviosité.

Cependant dans d'autres régions on ne peut négliger l'influence d'un certain nombre d'autres facteurs :

a) Les gradients sont souvent quasi nuls (Sunderbans, Pays-Bas) ou bien dans d'autres directions (levée naturelle → cuvette).

b) La pluviosité peut dépasser l'évaporation.

c) La genèse géohydrologique (transgression et régressions) conditionne également la répartition latérale et artificale des salinités.

M. SCHOELLER : Oui, ce que je viens d'exposer suppose que la hauteur d'eau évaporée soit supérieure à la hauteur d'eau de pluie infiltrée.

Vous parlez ici des phénomènes de concentration par dissolution. J'ai d'ailleurs fait un travail portant sur deux cas :

a) Sa concentration par dissolution dans un terrain non lessivé en amont;

b) Sa concentration par dissolution dans un terrain partiellement lessivé en amont.

Ce travail a paru dans la *Revue du BRGM* de Paris (M. Schoeller, 1964).

Dans le cas des phénomènes géohydrologiques quand l'eau salée monte, elle repousse l'eau douce vers le haut, mais elle passe plus rapidement au centre des pores que sur leurs bords et plus rapidement à travers les gros pores qu'à travers les petits. Il reste donc de l'eau douce sur les bords et dans les petits pores. Cela conduira à un mélange des deux eaux; quand l'eau salée redescend, il reste de l'eau salée accrochée aux bords des gros pores et dans les petits pores. Elle se mélangera avec l'eau douce.

Quand la limite entre l'eau salée et l'eau douce ne bouge pas, il y aura aussi une zone de transition faible due à la diffusion.

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Interaction of river and sea water in the absence of tides

L. S. Borichansky and V. N. Mikhailov.

INTRODUCTION

Observations carried out in the mouths of rivers show that the discharge of a river into a water body (sea or lake) takes place in the form of a turbulent flow gradually expending itself in the basin waters. Making a diagram of the spreading of a river current in a basin is of great interest for determining the outlines of the river current with a different relief of the bottom of the basin, distribution of velocities in the current intermixture of river and sea water, calculation of the variations in the water's salinity and turbidity along the current, etc. The present paper describes the calculation of current velocities, salinity and horizontal patterns of the current in coastal waters of a tideless river mouth.

CALCULATION OF VELOCITIES IN THE RIVER CURRENT IN COASTAL WATERS

Main characteristics of the river current in the sea

The following main forces affect the river current in the coastal waters at the river mouth: the friction forces on the lateral surfaces of the current, friction on the bottom (when the current touches the bottom) and inertia. Since the water surface is approximately horizontal in the water basin the effect of the gravity in the current (in contrast with the stream in the river bed) is negligible. Therefore, the river current in the coastal waters appears to be inert and the balance of the current is provided mainly by the equilibrium of the resistance forces (friction) and inertia.

A differential equation of the movement of a stream current in the coastal waters may be written as follows:

$$V\frac{\partial v}{\partial S} = -\frac{2f_1v^2}{b} - \frac{f_2v^2}{h} \qquad (1)$$

where V = medium velocity of the current, b and h = width and depth of the current, f_1 and f_2 = resistance coefficient on the lateral surfaces of the current and on the bottom.

Change of water velocities along the current

Integration of equation (1) with some assumptions gives the following equation:

$$V = V_0\,\frac{\bar{f}_2\,b_0h_0}{e^{2\bar{f}_2S/h}\cdot(2\bar{f}_1\bar{h}^2 + \bar{f}_2\,b_0h_0) - 2\bar{f}_1\bar{h}^2} \qquad (2)$$

where S = distance from the initial section, $\bar{h}$, $\bar{f}_1$ and $\bar{f}_2$ = mean values of the corresponding parameters at an integration portion, V_0, b_0 and h_0 = velocity, width and depth at the initial section. In obtaining equation (2) the law of conservation of momentum in a current, QV = Const. or $V_0^2b_0h_0 = V^2bh$, was applied by I. M. Konovalov (1939). Comparison of equation (1) with the ordinary equation of unsteady water movement for rivers shows that coefficient f_2 may be expressed by means of the Shazy coefficient: $\bar{f}_2 = \frac{g}{C^2}$. Coefficient f_1 should be determined experimentally.

If the friction forces against the bottom are negligible ($\bar{f}_2 = 0$), equation (2) may be transformed into:

$$V = V_0\sqrt{\frac{b_0h_0}{4\bar{f}\;\bar{h}_S + b_0h_0}} \qquad (3)$$

If friction forces against the lateral surfaces of the current are negligible ($\bar{f}_1 = 0$), equation (2) may be transformed to:

$$V = V_0e^{-\bar{f}_2S/\bar{h}} \qquad (4)$$

Equations (3) and (4) might be directly obtained by integration of equation (1) with appropriate assumptions.

Equation (4), as laboratory observations and field studies have shown, perfectly reflects the character

of the velocity change along the transit part of the current (with a constant discharge).

Equations (2), (3) and (4) show that the mean velocity of a river current gradually decreases as the distance from the mouth increases.

LABORATORY AND FIELD STUDIES

The experiments carried out in the Laboratory of River Channel Processes of the U.S.S.R. Academy of Sciences, to test out the law of the velocity change in a current, have proved that the equations obtained may be used and made it possible to determine the friction coefficient on the side surfaces of a stream (Mikhailov, 1959).

The calculated change of the mean velocity of the current appeared to be close to the actual one (Fig. 1a). The velocity structure of the current and its horizontal outlines obtained by calculation were also close to the actual ones.

The experiments have also shown that the mean velocity considerably decreases along the current. The mean velocity on the stations along the current axis, and especially the maximum velocity along the current axis, decrease with a less intensity.

The research expeditions carried out by the State Oceanographical Institute in the mouths of the Danube and Kuban rivers made it possible to study some problems concerning the expanding of river currents in the coastal waters under actual conditions. For example, A. I. Simonov's observations (1960) in the mouth of the Kuban have shown that the distribution of velocities along the current may well be expressed by an exponential curve like that in equation (3) (Fig. 1b).

The next problems to be examined in the future under natural conditions should be the determination of resistance coefficients, the study of the spreading of a current under different configurations of the coastal bottom, the influence of the sea along the shore and the effect of tidal currents.

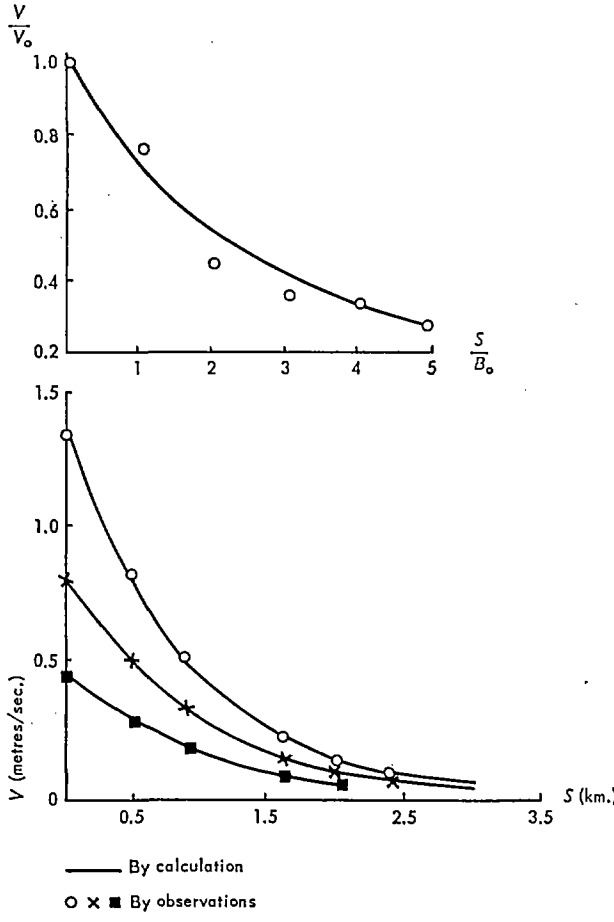

FIG. 1. Change of mean speed along a stream: (a) laboratory experiment; (b) Kuban mouth (after to A. I. Symonov).

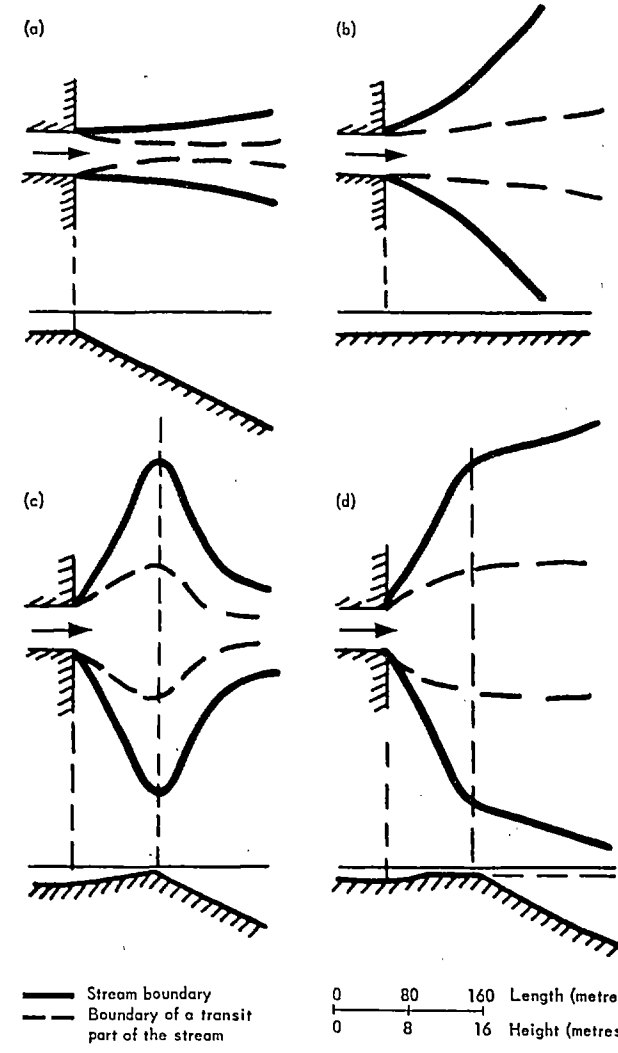

FIG. 2. Stream outlines obtained from calculation under the conditions: (a) depth in basin increasing; (b) depth in basin being constant; (c) bar; (d) bar and after-bar stream depths being constant.

HORIZONTAL OUTLINE OF THE CURRENT

An equation to measure the width of the current may be obtained from equation (2) by substitution of $V^2bh = V_0^2 b_0 h_0$. In the same manner, for two simpler cases (equations 3 and 4), it is possible to obtain the following:

$$b = \frac{4\bar{f}_1 \bar{h} S + b_0 h_0}{h} \tag{5}$$

$$b = b_0 \frac{h_0}{h} e^{\bar{f}_1 S/\bar{h}} \tag{6}$$

The horizontal outlines of the current were calculated, with the help of the equations obtained, for the following four cases: (a) the basin depth increases outward from the mouth; (b) the basin depth is constant; (c) there is a rise of the sea bottom (bar) in front of the river mouth; (d) after the bar the current depth is constant (analogous to the natural case when, due to the inflow of a stream into a basin with denser waters, the fresh water spreads only on the surface and the current depth remains constant). The conditions for calculation are: $Q_0 = 80$ cu. metres/sec.; $V_0 = 1$ metre/sec., $b_0 = 40$ metres; $h_0 = 2$ metres.

With this calculation four types of current spreading can be obtained and it is possible to draw the following basic conclusions (Fig. 2): (a) the greater the depth in a basin, the narrower the width of the whole current including its transition reach; (b) as the depth in the basin increases the transition reach of the current becomes narrower (equation 6); (c) a bar causes a sharp widening of the current; (d) the greater the roughness of the bottom the more swiftly the current widens.

The laboratory experiments have proved the existence of the first three types of current widening (Fig. 3). Studies performed in the mouths of the Mississippi (Scruton and Moore, 1953), the Danube, the Kuban and other rivers also prove the existence of the fourth type of current widening.

SALINITY DISTRIBUTION IN THE PART OF THE SEA IN FRONT OF THE MOUTH

A river discharge into the sea may be considered as a continuous freshwater source situated near the edge of the sea at the mouth. River water when flowing out of the mouth mixes with sea-water and freshens it. As the distance from the mouth increases the quantity of river water (in weight or volume) per weight or volume unit of sea-water decreases while its salinity increases.

Let us first consider a river with a single-branch narrow mouth as a continuous source of fresh water. Let us suppose that the sea has a constant but not great depth and that intermixture takes place through the entire layer of water; the concentration of fresh water in all points of the liquid vertical column being the same and equal to a mean (relative to the depth) concentration of river water.

Let us assume the co-ordinate system in which the x-axis coincides with the direction of the current, the y-axis is perpendicular to it, and the co-ordinate centre is on the sea edge of the mouth.

The distribution of the concentration of the fresh water from the continuously acting point source (Borichansky, 1961) satisfies the equation:

$$\bar{u} \frac{\partial C}{\partial x} = K_y \frac{\partial^2 C}{\partial y^2} \tag{7}$$

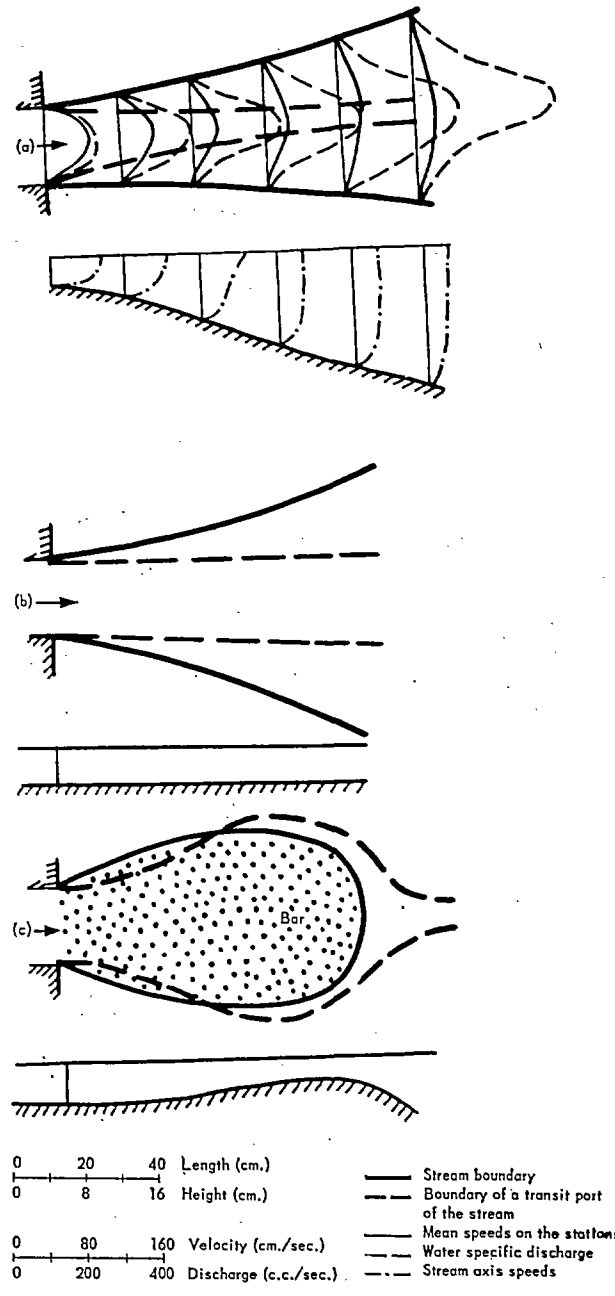

FIG. 3. Stream outlines obtained from laboratory experiments: (a) depth increasing along the stream; (b) depth in basin being constant; (c) bar existing before a stream delta.

Here $C(x, y)$ is the concentration of the fresh water in point (x, y), K_y is the coefficient of turbulent diffusion in the direction of the y-axis, and $\bar{u}$ is the current velocity averaged in time.

Thus, we have a river flow which spreads along the current and is washed out perpendicularly to it.

Simultaneously with the diffusion of the river water an exchange of pulses takes place between the river and adjacent sea-water, therefore the velocity of the river current decreases as the distance increases. It is possible to assume that the mean current velocity at a distance of x from the mouth $(x > 0)$ is determined by the expression:

$$\bar{u} = \bar{u}_1 \frac{x_1}{x} \tag{8}$$

where: $\bar{u}_1$ = current velocity at the x_1 distance from the mouth; boundary conditions $C \to 0$ at $x, y \to \infty$; $C \to \infty$ at $x = y = 0$; $h\bar{u} \int_{-\infty}^{+\infty} C(x, y)\, dy = Q$ for all $x > 0$; h = depth, Q = river discharge.

The solution of this equation satisfying the boundary conditions will be:

$$C(x, y) = \frac{Q\sqrt{x_1}}{hx\sqrt{2\pi u_1 K_y}} \exp\left[\frac{u_1 x_1 y^2}{2K_y x^2}\right] \tag{9}$$

Let us now consider the distribution of the river-water concentration in the parts of the sea in front of the mouth for a river with a wide mouth. Let us express the mouth width by $2a$ and the angle between the current direction and sea edge of the mouth by δ. The co-ordinate system centre is supposed to be in the middle of the mouth section.

The river with the wide mouth may be considered as a sum of elementary sources with the discharge

$$dq' = \frac{Q}{2a \sin\delta}\, dy'.$$

Concentration of the river water at the point (x, y) will be equal to:

$$C(x, y) = \frac{Q\sqrt{x_1}}{2ah\sin\delta x\sqrt{2\pi\bar{u}_1 K_y}} \int_{-a\sin\delta}^{+a\sin\delta} \exp\left[-\frac{u_1 x_1 (y - y')^2}{2K_y x^2}\right] dy'$$

$$= \frac{Q}{4ah\sin\delta\bar{u}_1}\left[\varnothing\left(\frac{a\sin\delta - y}{2}\sqrt{\frac{2\bar{u}_1 x_1}{K_y}}\, x^{-1}\right) + \varnothing\left(\frac{a\sin\delta + y}{2}\sqrt{\frac{2\bar{u}_1 x_1}{K_y}}\, x^{-1}\right)\right] \tag{10}$$

Here $\varnothing(t)$ = Kramp's function (probability integral). Expression (10) makes it possible to determine the concentration of river water in the pre-mouth part of the sea. In practice it is not the concentration of the river water but its salinity which is usually measured. The latter can be calculated by use of the formula:

$$S(x, y) = S(x_1, y_1)\frac{1 + C(x_1, y_1)}{1 + C(x, y)}$$

$$= S(x_1, y_1)\frac{1 + \frac{C_0}{2}\left[\varnothing\left(\frac{a\sin\delta - y_1}{2}\beta x_1^{-1}\right) + \varnothing\left(\frac{a\sin\delta + y_1}{2}\beta x_1^{-1}\right)\right]}{1 + \frac{C_0}{2}\left[\varnothing\left(\frac{a\sin\delta - y}{2}\beta x^{-1}\right) + \varnothing\left(\frac{a\sin\delta + y}{2}\beta x^{-1}\right)\right]}, \tag{11}$$

where

$$C_0 = \frac{Q}{2ah\bar{u}\sin\delta}; \quad \beta = \sqrt{\frac{2u_1 x_1}{K_y}}.$$

Let us next consider the case when observation points are located along the axis of the current $(y = 0)$, and assume that the current is perpendicular to the sea edge at the mouth $(\delta = 90^\circ)$. In this case the expression will take the following form:

$$S(x, 0) = S(x_1, 0)\frac{1 + C_0\,\varnothing\left(\frac{a\beta}{2}x_1^{-1}\right)}{1 + C_0\,\varnothing\left(\frac{a\beta}{2}x^{-1}\right)}$$

$$= S(x_1\, 0)\frac{1 + C_0\,\varnothing(Bx_1^{-1})}{1 + C_0\,\varnothing(Bx^{-1})} \tag{12}$$

where $$B = \frac{a\beta}{2}.$$

Let us assume that $K_y = k\bar{u}_1$; we may consider that coefficient k obeys the Obukhov-Richardson law, that is $k = Cl^{4/3}$. Here c is coefficient, l is a value characterizing the size of the observation area. Therefore we may regard the coefficient k—being different in different areas—as a constant in time when it is taken for one and the same area. As x_1 is constant, B may be considered unchangeable in time, and therefore value $\varnothing\left(\frac{\beta}{x}\right)$ is not changed from one measurement to another.

Value $C_0 = \frac{Q}{2ah\bar{u}_1}$ depends on river discharge Q and current speed $\bar{u}_1$. C_0 values can change from one measurement to another, therefore C_0 should be determined for every individual measurement. Value C_0 can be obtained from expression (12) having measured the salinity at two points $(x_1, 0)$ and $(x_2, 0)$. Value C_0 is expressed by the formula:

$$C_0 = \frac{S_2 - S_1}{S_1\,\varnothing\left(\frac{B}{x_1}\right) - S_2\,\varnothing\left(\frac{B}{x_2}\right)}, \tag{13}$$

where S_1 and S_2 are salinities at points $(x_1, 0)$ and $(x_2, 0)$ respectively.

Value B may be found in the following manner: value B is so selected from the studies performed at a number of stations located along the axis of the current $(y = 0)$ that the computed values of salinity at these stations would be in a rather good agreement with those measured there.

Having received value B and having determined value

C_0 from formula (13) we can obtain the salinity value for each measurement for any point located along the axis of the current.

To check the correctness of expression (12) and of all the adopted assumptions we took the results of the studies carried out at ten stations located along the northern coast of the Gulf of Finland. As is known, there is along the northern coast of the Gulf of Finland a current flowing from east to west, therefore we could assume that for those stations $y = 0$.

Values $\varnothing\left(\frac{B}{x}\right)$ were determined from the studies undertaken in 1922. Value B was taken as equal to 50 in calculations. Values C_0 were calculated from formula (13) on the basis of studies performed in 1935. In the formula x_1 means the distance from the sea edge of the mouth to the station of Tammio ($x_1 = 165.5$ km.); x_2 means the distance to the station of Russare ($x_2 = 407$ km.). Figure 4 shows that the computed values of the salinity coincide rather well with those obtained from the measurements. The mean error $|\Delta S|_{\text{mean}} = 0.18\ ^0/_{00}$.

Let us consider a more general case when the points where the observations were carried out are situated not along the axis of the current ($y \neq 0$); and the survey posts where values C_0 were determined are placed near to the axis of the current ($y_1 = 0$ and $y_2 = 0$). In this event the salinity in point (x, y) can be defined from the expression:

$$S(x,y) = \frac{S_1\left[1 + C_0\,\varnothing\left(\frac{B}{x_1}\right)\right]}{\dfrac{1 + C_0\,\varnothing\left(\frac{a-y}{2}\beta x^{-1}\right) + \varnothing\left(\frac{a+y}{2}\beta x^{-1}\right)}{2}}$$

$$= S_1\frac{1 + C_1}{1 + C_0 F(a,y,\beta,x)} \qquad (14)$$

where:

$$C_1 = C_0\,\varnothing\left(\frac{B}{x_1}\right); \quad F(a,y,\beta,x)$$

$$= \frac{\varnothing\left(\frac{a-y}{2}\beta x^{-1}\right) + \varnothing\left(\frac{a+y}{2}\beta x^{-1}\right)}{2}$$

From expression (14) it is possible to define F (a, y, β, x):

$$F(a,y,\beta,x) = \frac{1 + C_1 - \frac{S}{S_1}}{C_0\frac{S}{S_1}} \qquad (15)$$

It is possible to assume that F (a, y, β, x) changes little in time.

Thus, to define the salinity in any point (x, y) of the pre-mouth part of the sea one should: (a) determine value B from the observations carried out at a number of stations located along the axis of the current by one or several measurements preceding the measurement for which the calculation is being done; (b) by using formula (15) determine value F (a, x, β, y) from the observations at point (x, y) by one or several measure-

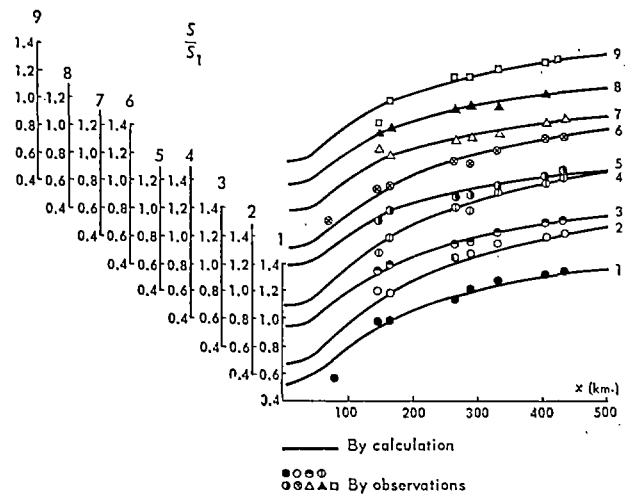

FIG. 4. Calculated and measured values of salinity in the Gulf of Finland. Figures stand for numbers of measurements.

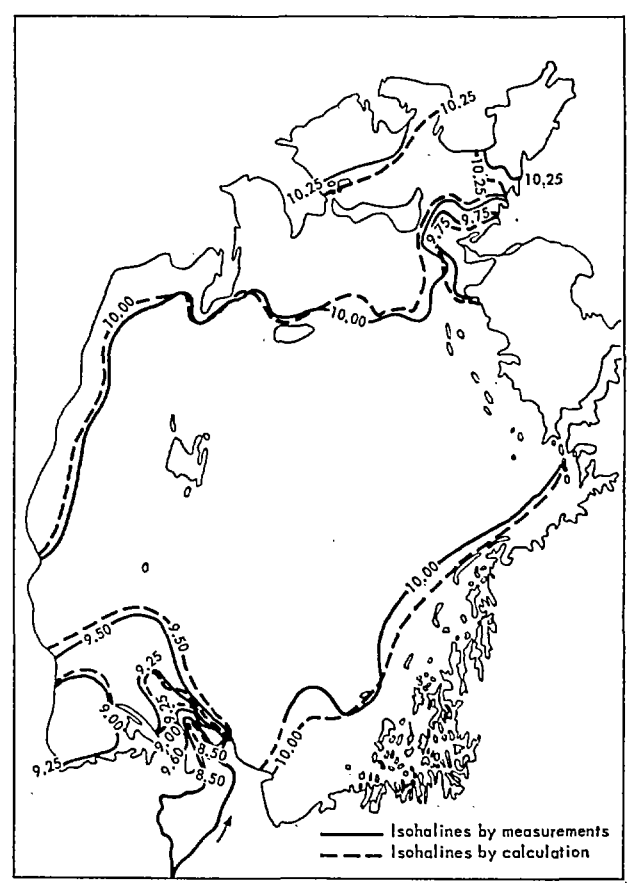

FIG. 5. Calculated and measured values of salinity in the Aral Sea (October 1958).

ments preceding the measurement for which the calculation is being done; (c) by using formula (13) determine value C_0 from the observations carried out at two points situated along the axis of the current by the measurement for which the calculation is being made; (d) put values C_0, $\varnothing\left(\frac{B}{x}\right)$, $F(a, y, \beta, x)$ and S_1 in formula (14).

To check it we used the results of the studies undertaken in the Aral Sea in 1957 and 1958 (six surveys). The checking was made on the basis of the studies carried out at 113 stations. Values B and $F(a, y, \beta, x)$ were determined from the studies for 1956. Value B is assumed to be equal to 25; C_0 values were determined from the studies made at points $x_1 = 48.1$ km. and $x_2 = 217.3$ km. Figure 5 shows that the calculated salinity isohalines (dashed) coincide rather well with those measured (continuous). The mean value of error $|\Delta S|$ mean $= 0.21$ $^0/_{00}$.

CONCLUSIONS

1. By solving the differential equation of the flow as regards a river current in a basin, functions for the calculation of the distribution of mean velocities in a current, as well as for the current horizontal outlines were obtained. The law of the decrease of flow velocity with the decelerating intensity was obtained by calculation and checked by the laboratory experiments and field observations.
2. The laboratory experiments and field observations have proved the actual existence of the previously calculated four types of current spreading which depend on the configuration of the bottom of coastal waters.
3. Considering a river as a continuous source of fresh water and solving the diffusion equation for turbulent conditions a method was obtained for calculating the salinity distribution in the part of the sea in front of the mouth for rivers with (a) a narrow mouth (point source) and (b) for those with a wide mouth (line source). The results were confirmed by observations.

Résumé

Interaction des eaux fluviales et des eaux de la mer en l'absence de marées (L. S. Borichansky et V. N. Mikhailov)

En résolvant l'équation différentielle qui exprime le mouvement d'un cours d'eau dans un bassin, on obtient des dépendances permettant de calculer la distribution des vitesses moyennes dans un cours d'eau et de déterminer la structure générale du courant. La loi selon laquelle la vitesse du courant diminue avec l'intensité de l'amortissement a été établie par le calcul, puis vérifiée par des expériences de laboratoire et des observations effectuées sur le terrain.

Ces expériences et ces observations ont confirmé les calculs en révélant l'existence de quatre types de structure du courant selon le relief du fond sur lequel se déplacent les eaux côtières.

En considérant un fleuve comme une source active continue d'eau douce et en résolvant l'équation relative à la diffusion turbulente, on a établi une méthode pour calculer, dans le cas des fleuves à embouchure étroite (source ponctuelle) et des fleuves à large embouchure (source linéaire), la répartition de la salinité dans la partie de la mer située devant l'embouchure. Les résultats ainsi obtenus ont été confirmés par les observations.

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Hydraulic scale models of deltas (including mathematical models)

V. N. Nagaraja

INTRODUCTION

Model investigations, whether with the help of hydraulic models, analogue models of mathematical models, will continue to be an indispensable tool for designers of engineering works. Their importance has not diminished with experience but, on the contrary, with the success resulting from the application of these model investigations, more and more recourse is being made to them for the solution of the most intricate problems of hydraulic behaviour which are generally not more than partially susceptible to rigid mathematical analysis.

Unquestionable results are obtained from hydraulic models for problems of spillways, etc., when the Froude number plays the dominant role. In the case of river-training problems involving mobile boundaries, erosion and sedimentation, curved and secondary flow, etc., very valuable results have also been obtained, but only with expert techniques of experimentation and experienced interpretation.

Deltaic areas feature, barring exceptional cases, a number—often a network—of channels in which hydraulic equilibrium is maintained by the tidal forces from the sea-end and by freshwater discharges from the drainage areas served by these channels. Any training measure, or control works, in such a system may be expected to interfere to a greater or lesser extent with this equilibrium. Conventional training measures which have proved successful in normal (one-way) rivers will often prove inadequate—or even harmful—under a complicated tidal system. It follows that the models meant for solving problems of deltaic areas must be even more complex than for the mobile-boundary problem (referred to in the previous paragraph) and involve more complicated and elaborate techniques of investigation and interpretation aided with engineering judgement.

While the importance of model investigation has been widely recognized, it should be emphasized that it is only an aid to analytical and mathematical processes and cannot be expected to produce results like a sausage machine. It should be used only to fill the gaps which cannot be covered by analytical work and, in certain cases, to obtain visual confirmation of results otherwise obtained. Just as mathematical techniques are inadequate for problems involving curvilinear and secondary flow, scour and erosion, etc., so also models have certain limitations which cannot be overlooked. These limitations, not being too obvious, call for expert understanding.

PROBLEMS ENCOUNTERED

The problems generally encountered in deltaic areas fall into one or other of the following principal classes: (a) maintenance or improvement of navigation channels, improvements in bars, crossings, etc.; (b) evolution and evaluation of measures for mitigating problems of drainage, floods, etc., due to flow from rivers, etc.; (c) determination of closure techniques for estuarine inlets for optimum results; (b) effect of closures of inlets on the tidal mechanism of estuaries, on littoral problems along the coast, etc.; (e) effects of interaction of freshwater discharges and tidal flow.

These give only a broad indication of the main types of problem that are likely to arise, and they would have to be considered either together or separately depending upon the particular situation encountered.

HYDRAULIC MODEL TYPES

In practice, the types of models used are the following: geometrically similar models (two-dimensional models) and vertically exaggerated models (three-dimensional models), which can be either (a) the complete model, or (b) the truncated model. Vertically exaggerated models can have either a rigid boundary or a mobile boundary.

Geometrically similar models have very limited

application in deltaic problems. They can be used for the determination of flow conditions—scour, etc. —resulting from artificial structures, coefficient of discharge, pressure distribution, etc. The model generally presumes two-dimensional flow.

The three-dimensional model covers a large spatial area (entry and exit areas as well as the problem zone) and limitations of space, model discharge, etc., impose very small scale ratios. Hence, the vertical scale is exaggerated to such an extent as to obtain measurable depths and effective velocities, at the same time providing the model with simulative friction. There appears to be no general limit to this exaggeration of the depth scales, particularly in rigid models; but in mobile models for one-way rivers experience has given best results with vertical exaggerations of about 5 to 8. In some cases where it is difficult to assess the "scale effect" resulting from imposed scale-distortion, recourse is made to repeating the investigation with different vertical exagerations—the horizontal scale remaining unchanged—and extrapolating results with engineering judgement. In other cases where it is difficult to "prove" the model with practicable horizontal and vertical scales, a further distortion by way of slope exaggeration has also been attempted. Vertical exaggeration involves slope exaggeration and further superimposition of slope exaggeration by "tilting" can be justified only on grounds of expediency.

With such scale distortions, necessitated partly by expediency and partly for conformity of behaviour of model to prototype, it is clear that the technique of interpretation of model findings must be based on long engineering experience of models and prototypes; and, unless the investigation is in the right hands, undependable conclusions and recommendations may result. This should be guarded against.

DATA REQUIRED

The data required would depend esentially on the problem and the scope of investigations. For hydraulic models dealing with estuarine channels, the following data would be required: survey data of plan and cross-sections of the channel or channels, bank line configuration, etc.; representative water levels, velocities and discharges at representative stations; representative silt and salinity data; data of upland discharges; details of existing structures; tidal data (high and low waters, ranges, curvature, etc., up to the tidal limit); data of surges, bore tides, etc., if any; data regarding the petrographical constitution and movement of bed material at vulnerable reaches.

More often than not the data will not all be available, and, even where available, will not cover long or adequate periods. Whether it is the hydraulic model or the mathematical model, the importance of accurate and adequate data cannot be overemphasized—after all, the model cannot be more accurate than the data that is fed into it.

THE SCALE AND THE BED MATERIAL FOR THE MODEL

As indicated above under "Hydraulic Model Types", the horizontal scale is fixed with due regard to the space and discharge available for the model *vis-à-vis* the area which is to be reproduced. In cases where it is necessary to have a model reproducing a long length of an estuary or estuaries—say up to the tidal limit—a small horizontal scale is unavoidable. If, however, the length of the estuary or estuaries is small or the model can be truncated, a larger scale is possible.

Having fixed the horizontal scale from the above considerations, the vertical scale is so fixed that (a) the resulting water levels and velocities are measurable, and (b) in the case of mobile bed models adequate tractive forces are generated so as to simulate the bed changes observed in nature.

Regarding the bed material to be used in mobile bed models a wide choice exists. In the case of tidal models the right choice is more important than in the case of one-way river models. Sand of selected grade will do for ordinary river models as well as for some tidal models, but some lighter material has also been found useful for the latter: graded coal dust, synthetic plastic materials, gilsonite, treated sawdust, crushed walnut, etc., have all been used and often found satisfactory, but the best results are obtained with very fine, non-cohering sand.

PROVING THE MODEL

The basic test of the fidelity of the model is its ability to reproduce conditions observed in the prototype: water levels, slopes, velocities, bed movements, etc. If these are found in the model to conform to prototype, it is said to have been "proved". Then it is hoped that the model would indicate, at least qualitatively, what is likely to happen under certain imposed situations. The proving procedure may call for certain adjustments of the vertical scale and the bed material. It may also involve compromising on the non-reproduction of some minor features observed in nature if they are not likely to affect the conclusions. It may further necessitate devices—copper strips, nails, etc.—for adjusting boundary friction. It is clear that for dependability of the model, prototype data must also be dependable and adequate.

In tidal models, the reproduction of tides is the first and the most important step in proving. Tidal data is generally available and, except in special problems, only one single average or representative tide is repeated for as many times as the total number of tides is to be reproduced. The classical Severn experiments by Gibson were done this way. When flood

or ebb features have to be emphasized, the representative tide will have a flood or ebb bias respectively. When both upland discharge and tides have to be taken into account, the bias will again be dependent on the problem. In short, the scope of the problem and the known limitations of the model condition the choice of the tides to be reproduced in the model.

In certain estuaries where the pattern of shoaling, etc., depends on the interaction of fresh and salt waters, reproduction of salinity in the model might become necessary, and recent investigations tend to support the view that for correct reproduction of conditions in such estuaries salinity has to be reproduced in the model preserving the same salinity pattern as in the prototype, notwithstanding the scale (Price and Kendrick, 1962).

TIDAL REPRODUCTION IN MODELS

When the model extends to the tidal limit, the tides will have to be produced from the sea-end only. If, however, it is a truncated model where both the end reaches are tidal, arrangements have to be made for tidal reproduction at both ends (Nagaraja, 1950). Obviously the operation at the two ends has to be co-ordinated with correct time lags and differences in tide levels.

The usual arrangement is to control the discharge (and hence the levels) in the model with the help of valves, gates, etc., operated manually or automatically so as to ensure the desired tide cycle.

It is always difficult to assess the effects of structures on the tides unless obviously they are such as not to have any effect at all or bring about a total closure so that, in either case, the boundary conditions are defined previously. This should be kept in mind especially in truncated models where the end-tides, discharges and velocities are supposedly known beforehand.

In the Central Water and Power Research Station, Poona, both the full-length and the truncated models have been adopted very successfully. The most satisfactory arrangement evolved after years of experience is to allow an adequate discharge into the tidal chamber where a controlled by-pass arrangement ensures the desired discharges into the model, depending upon the tide to be reproduced. The by-pass arrangement is a set of openings controlled by movable gates. The gates are often operated manually, in preference to an automatic arrangement, since with personal judgement the operation of the gates can be carried out very precisely. However, since the success is dependent on the skill and alertness of the operator, equipment is also used for automatic reproduction of tides.

In any automatic tidal control, the instantaneous water level in the model (given by a float) is always compared with the water level corresponding to the tide to be simulated in the model (given by a cam or a pointer following a prescribed curve). Opposite signals are obtained depending on whether the actual level in the model is higher or lower than the desired level. These signals, after proper amplification, are made to control the direction of operation of the gates in such a way that the error is reduced to the minimum. Such an "on-off" control results in excessive hunting and must be properly stabilized. An element of "anticipation" should also be incorporated.

The technique (CWPRS, 1959, p. 380-2) permits 90 per cent of the discharge to be controlled in a regular cyclic manner to give a saw-tooth curve and only the remaining 10 per cent discharge is corrected to get the final tidal curve.

PROVING FOR BED CHANGES

Since the problems generally relate to changes in the 90 per bed configuration (by silting and scouring and bar formation) it is desirable to understand under what conditions a rigid model would suffice and when a mobile bed model is necessary. At the outset it must be admitted that investigations with mobile bed models of tidal rivers are extremely complicated and success is more difficult to achieve than in the case of one-way rivers. The ever-varying nature of the tide, the changing pattern of upland discharges, the interaction of salt water and fresh water, the varying velocity distribution curves, and interferences caused by dredging and other conservancy activities—all these factors call for a vast amount of data which are generally lacking. Even if the data become available, proving the model for all these factors is almost impossible. Therefore, it is usual to avoid investigations with a mobile model. The rigid model is easier to operate and by successive superimposition of the anticipated changes in the bed and experimentation, it is possible, under special circumstances, and within limits, to obtain dependable indications. For instance, extensive velocity observations in the rigid model can throw light on zones subjected to silt deposition or scour. With the help of injection of light material (sawdust, crushed coal, gilsonite, etc.), areas susceptible to deposition can also be traced. If, however, bed changes are the problem, a mobile bed model is required, and one should not expect to reproduce in the rigid model all the changes that are likely to take place in nature. Trends, however, can be reproduced and they would afford valuable information regarding remedial works.

There are cases where tidal levels are important. For instance, a closure operation of an estuary can bring about far-reaching changes in the tidal system of the estuary, with little change in the over-all channel characteristics. In such a case a rigid model is likely to prove adequate.

LIMITATIONS OF HYDRAULIC MODELS

With a large number of variables governing deltaic channels, the control of the model is complicated and,

though very often satisfactory, proving it takes time and presents serious difficulties. Changes in tidal channels are periodic, depending upon the tidal conditions, and, unless the whole tidal period is run, the investigations will not be complete. Thus, the investigations are protracted and, if a large number of alternatives have to be investigated, the investigations will inevitably take a long time.

Deltaic areas are often very large, covering over 100 sq. miles at times, and the biggest model that can be designed will prove to be too small for detailed observations; conversely, if a model has to be built so that detailed observations are possible, the size of the model would be unmanageable.

If the Sunderbans delta had to be investigated, with rivers over 100 miles in length (the Hooghly is about 200 miles up to the tidal limit, the Matla about 100 miles) and with inter-connected criss-cross channels forming a maze of network, the complexities of a hydraulic model can well be imagined. It would still be required and used for limited problems; but, for the over-all problem, recourse would have to be made to a mathematical model or an analogue model.

ANALOGUE MODEL

The analogue model may represent either an electric analogue or the magnetic analogue. The electrical analogue is based on the analogue of fluid flow in flow-resistance channels and electrical flow through resistance-conductors. The success of the analogue model depends on the correct choice of non-linear conductors for the model, although success has been achieved in certain cases with the use of linear capacitors and inductors, for instance, in cases where wave amplitude is negligible in comparison with the water depth and the channel sides are vertical (Einstein and Fuchs; Glover *et al.*, 1953; Van Veen, 1949). As a result of investigations on the delta region of California, a new type of square-law resister was developed which would bring the analogue model much nearer to the hydraulic model (Harder, 1957).

There is no known example of the use of the magnetic analogue for deltaic problems.

THE MATHEMATICAL MODEL

In spite of the great cost involved, the hydraulic model has continued to occupy a special place mainly because of the difficulties of solving the basic equations of fluid motion. Unfortunately, of the important branches of hydraulics, the least amenable to mathematical analysis is the propagation of waves in open channels—flood waves in river systems and tidal waves in estuaries. But for the advent of electronic computers (digital computers and differential analysers), this could not have been undertaken except for the simplest of cases. The electronic computer has, however, made possible the rapid computation of equations with a large number of variables.

The basis of the mathematical model lies in the solution of the fundamental differential equations of flow. While considering more or less clearly defined tidal channels, the flow can be considered one-dimensional and, except in cases like bore tides, the vertical acceleration may be ignored. The basic equations are:

$$\frac{\partial Q}{\partial x} + B\frac{\partial h}{\partial x} = 0 \qquad (1)$$

(continuity equation) and

$$\frac{\partial h}{\partial x} + \frac{1}{gbd}\frac{\partial q}{\partial t} - Q\frac{(b+B)}{gb^2d^2}\frac{\partial h}{\partial t} + \frac{Q\,|Q|}{c^2b^2}d^3 = 0 \qquad (2)$$

(dynamic equation)

where Q = discharge, positive in the downstream direction;
h = height of water surface above datum,
x = length along the channel,
t = time,
B = width of water surface,
b = average width of cross-section defined by $A = bd$,
d = average depth of water corresponding to level h,
g = acceleration due to gravity,
C = Chezy coefficient.

The success of the mathematical model depends on its facility for solving the dynamic equation. The simplest case, of course, would be that where the tides are of the simple harmonic type—and the success of the work done in India in connexion with certain closure problems of the Sunderbans area is due to this assumption and a justification thereof. In such a case, the tidal movement is a periodic phenomenon with a period of about 12 hours and 25 minutes and can be approximated with the help of the Fourier analysis in the form:

$$h(x,t) = h_0(x) + h_1(x)\cos(\omega t + \alpha_1(x)) + h_2(x)\cos(2\,\omega t + \alpha_2(x)) \qquad (3)$$

where $h(x, t)$ = water level at any point x at time t,
ω = angular velocity $= \frac{2\pi}{T} = 1.4504 \times 10^{-4}$ radians/sec. approximately (T being the total period of the tide cycle),
$h_0(x)$ = main water level at the point x,
$h_1(x)$ = amplitude of main tide, called M_2 tide,
$h_2(x)$ = amplitude of the first overtide, called M_4 tide,
$\alpha_1(x)$ = phase angle of the main tide,
$\alpha_2(x)$ = phase angle of the first overtide. and so on.

Similarly, Q may also be considered as a periodic function which can be expressed as

$$Q(x,t) = q_0 + q_1(x)\cos(\omega t + \beta_1(x)) + q^2(x)\cos(2\,\omega t + \beta_2(x)) \qquad (4)$$

where q_0 is the upland discharge (independent of x), $q(x)$, $q_2(x)$ are the amplitudes, and $\beta_1(x)$, $\beta_2(x)$ are the phase angles of the different tides M_2, M_4 in Q. In actual practice, depending on the simplicity of the problems, the terms beyond the M_4 tide may be ignored. In many cases, however, like the Hooghly for instance, the overtides are pronounced, and the equations will naturally be more complicated.

Various artifices are adopted for solving these equations. Developed by Dr. Dronkers (1955) in the course of the tidal computation for the Dutch reclamation works, they cover a very wide range of cases. By a judicious use of the Fourier analysis and the complex function, the equations are reduced to manageable proportions and forms. The method of iteration was used with advantage for the evaluation of the M_2 tides in the Sunderbans problem.

When the tides are not of the simple harmonic type, it is often possible to resolve them into two or more components which by themselves are simple harmonic with separate periods and phase lags. For instance, while designing curves for the tide-reproducing mechanism for the Hooghly model, at Poona, it was shown that the tides at Saugor, at the mouth of the Hooghly estuary, could be satisfactorily resolved into two harmonic constituents. It must be emphasized that the influence of the overtide increases inside the estuary and would not, therefore, admit of a resolution into two components. A larger number of components may bring about satisfactory results but the computations are tedious.

It is apparent from the nature of the dynamic equation (equation 2 above) that the channel section is taken to be equivalent to a rectangle and that the correct choice of the friction factor (Chezy coefficient) is called for. This procedure of evaluating a representative rectangle and friction factor is called "schematization". This corresponds to adjusting the hydraulic model for "proving" it. By a correct adjustment of the friction, bed material and scales, it would be possible to obtain values of Q, v, d, etc., observed in the prototype; conversely, for proving the mathematical model, a correct schematization is inescapable.

Correct schematization presupposes dependable prototype data to check the results—data of discharges, velocities and water levels. Theoretically, at least, experimenting with the equivalent geometry of the cross-section and the Chezy coefficient one can hope to deduce the desired levels. Since these parameters are known to vary with tides, what has been derived for one tide may not prove satisfactory for another. In particular, the friction coefficient is not a simple function and it may vary from reach to reach. For instance, in the West Sunderbans model, the value of C varied from 50 to 60 among the 24 reaches selected. In the case of the Panama sea-level canal, a value of 146 gave end-results correctly. In other words, the value of C has to be determined for each reach and for each stage besides schematizing each of the sections to conform to a rectangular channel. This will naturally result in so many variables that any traditional mathematical or analytical process must appear impracticable. The electronic computer has made this work practicable.

The fantastic speed of computation, the large number of variables that may be simultaneously tackled and the rapidity with which it would be possible to study several alternatives, carrying out repetitive computations with the help of an electronic computer have added to the versatility and dependability of the mathematical model. In many cases it scores over the hydraulic model in cost also. By the achievements scored with the electronic computer, the problems of deltaic channels are classed amongst the simple problems of engineering science.

LIMITATIONS OF MATHEMATICAL MODELS

While the principal attribute of an electronic computer is that equations which would normally take several months and years to solve can now be solved within minutes and hours and with even greater success, the success depends, however, on proper "programming" which must be done beforehand. This involves schematization, determination of end-conditions, etc., and deriving the various constants for obtaining known water levels, discharges, etc. In other words, the essential prerequisites for the mathematical model are the same as those for the hydraulic model. Until recently, the programming was about the most complicated part of this work, but programming has now been simplified into a rational technique.

The laws governing the various parameters in the case of rigid-boundary channels can be deduced with some approximation, but those governing mobile-boundary channels, movement of shoals, scour and erosion, etc., are still elusive. Mathematical models are, therefore, promising in the former case only, but have also been successfully used in the determination of water levels in reservoirs and channels during floods and operation of control work.

In the case of problems relating to silt and scour, schematization of cross-sections required for the mathematical model would be an over-simplification since it is not the "average" condition that governs the flow, but the velocity pattern in the whole section. Curvilinear flow and secondary flow assume great importance and only a hydraulic model can reveal the true picture in cases where the departure from average conditions is significant.

It must be apparent that there is no conflict between the mathematical model and the hydraulic model or the analogue model. These are complementary to each other and they should often be used together so that information can be collected from one for use in the other. As mentioned above, local problems and problems involving velocity distribution, etc., must

be solved by hydraulic models; over-all average changes of a complete system can be assessed by a mathematical model. Each problem must be taken on its own merits and the appropriate model, or combination of models, used for its best solution.

SALINITY AND MODEL TECHNIQUE

It is recognized that the interaction of fresh water and salt water generates certain secondary effects, which are generally very difficult to reproduce in models. It is observed that in some of the American and Japanese estuaries where the upland discharges are very large as compared to the tidal influences, the saline water penetrates upstream along the bottom in the form of a wedge. At the other extreme where the upland discharges are relatively very small complete mixing takes place. There are intermediate cases also of partially mixed flow. Density differences generate a certain pattern of density currents within the body of water and influence the sedimentation process. It is, therefore, sometimes held (Price and Kendrick, 1962) that models fail to reproduce the velocity pattern unless salinity is reproduced in the model. It has also been found from experience that, notwithstanding the vertical exaggeration of the model, the same density gradients as in a prototype would yield satisfactory results. Thus, although it may be fully justified theoretically, in actual practice, however, the use of saline water might be impractical and inordinately expensive and, considering the various other limitations of the model, such a refinement might not improve the overall efficiency of the model significantly. There are undoubtedly cases where the primary flow conditions and velocity patterns are preponderant in effect in comparison with the negligible effects of the secondary conditions. Thus, it would appear that reproduction of salinity is not a universal requirement or mandatory. A large number of problems have been solved successfully without this refinement.

Where density currents are observed, it would be necessary to collect extensive prototype data of salinity and velocity at various depths and verticals and sections. This calls for an elaborate observation programme and would often be restricted by, or cause interference to, shipping and other activities. Extensive investigations have been made in the Mississippi, Savannah, Columbia and other estuaries in the United States and in the Tone and the Gokase estuaries in Japan, where density currents were, *prima facie*, an important likely cause of the siltation. These observations provide revealing data about the presence or absence of density currents and a useful basis for understanding the consequential sedimentation process.

TYPICAL EXAMPLES OF MODEL STUDIES IN INDIA

The intention here is to recapitulate briefly some of the typical examples of model studies undertaken in India in order to throw further light on some of the remarks made so far.

Hooghly river models

The Hooghly river models at the General Water and Power Research Station, Poona, provide useful examples of tidal models wherein complicated tidal problems are being solved.

Hooghly estuary model (scale 1 : 2,000, 1 : 160). In this model extending from Saugor (sea end) to Bansbaria, the following studies were made:

1. Improvement of Fulta James and Mary reach. The very peculiar configuration of this reach and the existence of two bars had made this reach one of the biggest obstacles to navigation.

   The studies revealed that a recession of the existing protrusion at Fulta point and a certain reclamation on the opposite bank was the solution to the problem.
2. Head-water discharge to neutralize the salinity of the Hooghly waters at Calcutta. The salinity problem in the Hooghly has become acute, and drinking water supply and water for industries are seriously affected, warranting immediate remedial measures. A solution lies in getting the required freshwater discharge to keep the salinity within potable limits. Experiments were conducted reproducing the salinity in the model and the optimum upland discharge was arrived at from various trials.

Of the various other tests that have also been conducted in this model the following are important: (a) Balari Bar—improvements of depths over the bar; (b) finding out suitable spots for disposal of the dredged spoil so that it would not return to the navigable channel.

Port model of the Hooghly (scale 1 : 300, 1 : 60). Since the estuary model was inadequate for investigations concerning the upper reaches, another truncated model, on a larger scale, extending from Moyapur to Konnagar, about 10 miles above Calcutta, was constructed. The important investigations carried out in this model include those for the Sankaral, King George Dock and Ahiritola reaches, concerning navigation.

The problem at Sankaral was, very briefly, as follows: the progressive erosion of the Akra bank by flood flow resulted in a widening of the river at Sankaral bight accompanied by the formation of the Sankaral Sands. The ebb and the flood followed separate channels. During freshets the ebb predominates and more than adequate draught is available, but during the dry season the flood channel tends to develop through the Sankaral Sands to the detriment of navigation. With the progressive formation of this channel, the main navigation channel along the Sankaral bight has silted, resulting in shallower depths. Model studies were thus aimed at finding measures to push the flood away from the Akra bank and build up the Sankaral Sands more easily and

extensively. The experiments helped in evolving a correctly oriented spur of the requisite length which reduced the divergence of the two channels.

Rigid bed model of the Hooghly from Balari to Swarupganj (scale 1 : 600, 1 : 50). This model was constructed with the express purpose of investigating the effect of upland supplies on the velocities along the Hooghly estuary. The increase in ebb velocities and the decrease in flood velocities with different quantums of upland discharge were studied.

Mathematical model of the west Sunderbans. The reclamation programme of the Sunderbans area in West Bengal involves the closure of certain estuarine inlets. With about two years' prototype data of cross-sections, discharges, velocities, etc., of the system, a mathematical model was evolved at the River Research Institute in consultation with Dr. Dronkers of the Netherlands. Eight alternative closure programmes were considered and the effects on tides, velocities and discharges were computed by the harmonic method, limiting the computations to the M_4 tide. The M_2 tides were assessed by an iterative process. Since the tides in this region are almost simple harmonic, these simplified assumptions were justified.

The study of the Hooghly involves greater complications and the work has now been taken up by the Calcutta Port Commissioners.

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Résumé

Les modèles hydrauliques de deltas, y compris les modèles mathématiques (V. N. Nagaraja)

Lorsqu'il ne suffit pas, pour trouver la solution de certains problèmes, de les soumettre à une analyse théorique, on a recours à des modèles. Cependant, ceux-ci sont simplement des auxiliaires destinés à faciliter la compréhension des phénomènes, et leur emploi ne permet pas de se passer du jugement ou du diagnostic des techniciens. Les problèmes que pose la mise en valeur des zones deltaïques ne peuvent généralement pas être résolus sur la base de considérations purement théoriques, et ils doivent, en raison du grand nombre d' « inconnues » qui entrent en jeu, être étudiés à l'aide de modèles.

On peut citer parmi ces problèmes :

a) Ceux qui ont trait à l'entretien des chenaux navigables dont la profondeur va en diminuant (et aussi parfois à l'interaction entre l'eau douce et l'eau de mer);
b) Ceux qui ont trait à la salinité excessive de l'eau des estuaires et aux effets de cette salinité sur la végétation, sur les poissons, sur les activités industrielles, etc.;
c) Ceux qui sont liés à la protection contre les inondations, et à ses effets sur le mécanisme des marées, les lits des cours d'eau, etc.;
d) Ceux qui résultent de la fermeture de certains bras fluviaux dans le cadre des programmes de mise en valeur des deltas;
e) Ceux qui ont trait à l'influence que la fermeture de certains bras ou estuaires peut exercer sur les bras ou estuaires voisins;
f) Ceux qui ont trait aux effets qu'exerce sur le littoral la fermeture de certains bras fluviaux;
g) Ceux que pose l'usage de vannes, de robinets-vannes, etc., pour le drainage et la lutte contre les inondations.

Le choix du modèle et des méthodes de recherche à employer dépend de la nature du problème à étudier. Il existe différents types de modèles, à savoir :

1. Le modèle à trois dimensions, qui représente la totalité de la zone comprise entre la mer et le point où la marée cesse de se faire sentir;
2. Le modèle qui ne reproduit qu'une portion déterminée de cette zone;
3. Le modèle en coupe;
4. Le modèle mathématique.

Pour les études qui portent, par exemple, sur l'interaction de l'eau douce et de l'eau saline, sur la diminution de profondeur des chenaux navigables, sur les problèmes de salinité, etc., les modèles hydrauliques peuvent rendre de grands services. En vue de résoudre des problèmes particulièrement complexes, comme ceux qui ont trait à l'influence que peut exercer sur le mécanisme de la marée la fermeture de certains bras fluviaux, il convient d'utiliser des modèles mathématiques. Cependant, dans le cas de certains problèmes qui concernent l'hydraulique des milieux aux limites mal définies, les modèles hydrauliques demeurent, pour le moment, préférables aux modèles mathématiques, car la schématisation et la « programmation » de ces derniers soulèvent de nombreuses difficultés qui n'ont pas encore été réglées. Les modèles mathématiques sont des instruments de travail très précieux du fait qu'ils permettent de résoudre rapidement des

problèmes très divers, de prendre simultanément en considération un grand nombre de variables, de passer en revue toutes les solutions possibles et de répéter les différentes opérations. Chacun de ces deux types de modèle a ses avantages propres, et c'est à l'ingénieur qu'il appartient de choisir entre eux en fonction des facteurs techniques et économiques qui entrent en jeu.

A la Central Water and Power Research Station de Poona, on a étudié, à l'aide de modèles, divers problèmes relatifs à l'un des principaux estuaires de l'Inde, celui de l'Hoogly, y compris notamment les questions suivantes :

a) Niveau hydrostatique nécessaire pour neutraliser la salinité à l'usine hydraulique de Palta.
b) Mesures de drainage pour le Fulta James and Mary Reach.
c) Problèmes concernant les opérations de dragage ou autres travaux d'aménagement qui portent sur les barres, les passages, etc.
d) Amélioration du Balaribar.

Des modèles mathématiques ont, d'autre part, été employés à Calcutta pour des études concernant la fermeture de bouches d'estuaire peu importantes situées dans le Sonderband, et ses effets sur les estuaires voisins et sur le mécanisme de la marée.

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III

Vegetation

Végétation

Humid tropics and their vegetation

M. Qudrat-i-Khuda

The comparatively higher temperature and humidity of the humid tropics constitute a region of discomfort for the people who live there; but these conditions are very suitable for the vegetation and therefore this region of East Pakistan belonging to the humid tropics has created an environment rich in natural scenery with the luxuriant green vegetation of various tropical plants. It presents a very welcome sight to visitors and some have said that they had never seen such green lands and such an extensive cultivation of rice, as that which they saw during the summer months in this region. It is not my intention to give here a systematic description of the extent of our vegetation, but to present some general problems of the economic vegetation, vegetable sources of protein and medicinal plants of the region.

PROTEIN-DEFICIENT DIET

Among the inhabitants here, the lack of inclination for strenuous work has been attributed to the climatic condition of the humid tropics; but it is really mostly due to a lack of protein in their food rather than to the climate. A limited survey has shown that here people of different age groups do not get more than 45-48 per cent of the daily requirements in protein. From the researches that have already been undertaken in the East Regional Laboratories, this has been found to be the most prominent factor when considering the well-being of the people of this region. I do not intend to deal with the subject in detail, but will make only a passing reference to it, in so far as nutrition is related to the vegetable food of the people of the region. The problem, therefore, is that of the protein deficiency in the food of the people of the entire humid tropics, which is really an important factor needing careful attention.

Protein-deficient diets cause a lesser development of the nervous system. This has been shown very convincingly by Professor Platts, of the Human Nutrition Laboratories, Mill Hill (London). His work on animal feeding with protein-deficient diet very clearly demonstrated what could happen to men living on inadequate protein diets. This has also definitely established that protein deficiency leads to particular defects in the nervous system of the subject which may lead to many more troubles. With this end in view, the animal and vegetable diets of the people here were examined for protein. Many of the leafy vegetables, as well as pulses and seeds of various types which have been examined, hold promise for larger supplies of vegetable protein. Our work in this direction, however, is not yet completed; both seeds and leaves are being examined as sources of protein.

Rice is a very important crop of this region which perhaps grows the largest number of varieties of rice. Four crops are harvested during the different seasons of the year. During the rains one variety called "deep-water paddy" growing in low lands shows an extremely rapid growth. Sometimes, in order to keep its top above water level, it has been seen to grow more than an inch in twenty-four hours. The winter crops have yielded a large number of varieties of rice which differ in size and flavour. The land level varies from place to place and makes this particular region suitable for various crops of rice alone. Among the other crops, jute grows in a prolific way in both low and high lands. The low-land crop is harvested rather early but the harvesting of the high-land crop can be delayed considerably. Delayed harvesting may yield larger quantities of fibre, sticks and seeds.

VEGETATION FOR FOOD USE

The land is also suitable for the production of many other crops: sugar-cane and tubers, such as ginger and turmeric. Fair quantities of wheat, maize, vegetables, peanuts and oil seeds as well as pulses are all grown in different parts and in varying quantities. These provide raw materials for increasing the produc-

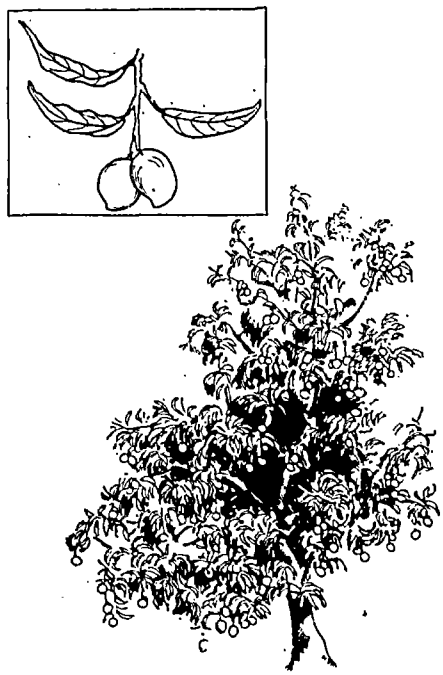

FIG. 1. Mango

FIG. 2. *Curcuma Zedoary.*

tion of vegetable proteins. The possibility of using the entire quantity of protein thus produced needs more elaborate investigation. This aspect of the vegetation cannot be included in the subject of the present paper as it would make it too long. The climate appears to be suitable for many tropical fruits such as mango, jackfruit, guava, coconut, pineapple and varieties of banana. A certain amount of attention has already been paid by the agriculturists to these well-known crops, but there is still a vast range of vegetation growing wild to which no particular attention has been paid; the present discussion will be confined to this latter group.

VEGETATION OF ECONOMIC VALUE

Among this natural vegetation some plants of economic interest either for their leaves, for their roots or for tubers have been found. No scientific investigation has, until now, been undertaken on the full utilization of such materials. Although fairly extensive cultivation is undertaken for production of sweet potatoes (Fig. 1), no organized effort has been made in the production of *Curcuma zedoary* (Fig. 2) which grows wild in many parts of the country and yields about 12 per cent of starch, whereas cassava, just introduced in some other parts of this region, produces about 14 per cent of its weight as starch. There are a good number of fruits, the more important of which have been mentioned earlier, that grow very well in this climate but as yet they are being used only to a limited extent. I should like to make a particular reference to two of the most important fruits of the region, namely pineapple and banana. The banana known as *amritsagar* (sea of nectar) is a very special kind of banana which is rather tender but with the most delicious flavour and taste; it is difficult to keep well for a long time. We are engaged in a series of researches on the progress of the ripening process of these fruits, and the results already obtained are rather encouraging. This suggests that it may be possible to control the rate of the ripening processes, at least to some extent, thus leading to a better preservation of the fruit during transportation from one place to another. It would then become possible to send out samples of this variety of banana with the more delicious types of mangoes and lichis to far-away countries. The local variety of pineapple (Fig. 3) is canned and found to keep quite well; however, further research might help in finding ways to keep the fruit as a whole for economic transportation. There are other fruits which grow extensively but owing to the difficulty of their preservation they remain within the country for local consumption only when they are in season. One such fruit is the well-known jackfruit (Fig. 4) some of which attain a weight of from 80 to 100 lb. each. Our efforts in preserving this fruit also appear to be quite successful. From the point of view of international interest in this fruit the future seems rather bright.

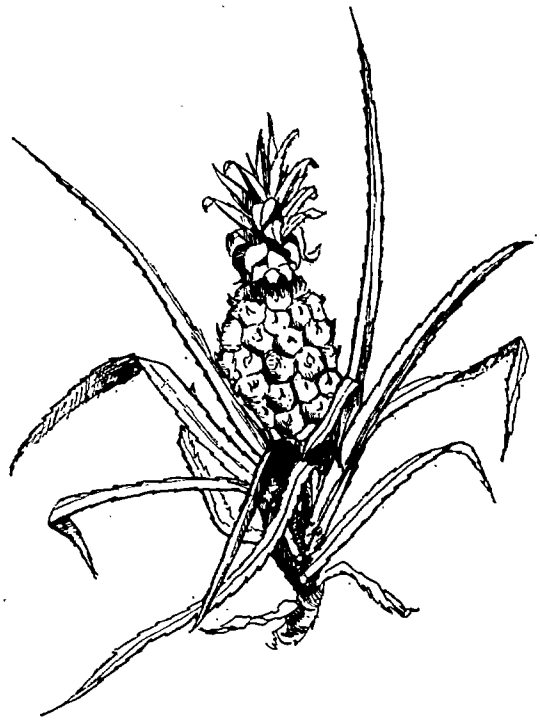

FIG. 3. Pineapple.

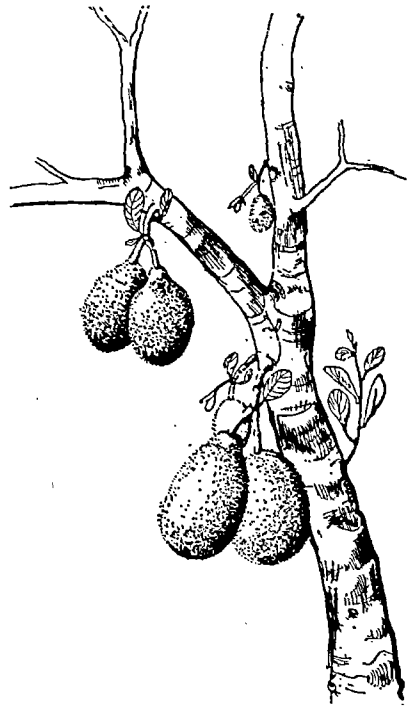

FIG. 4. Jackfruit.

MEDICINAL PLANTS

Particular mention should be made of the medicinal plants. Here is a land where, in the forest and even in inhabited localities, plants that have been used for their beneficial effect on human ailments for hundreds of years grow under ordinary conditions. They have, therefore, received much attention from the people interested in dispensing such medicines within the country. These age-old medicines have not yet lost their reputation. In that part of the country now known sa the Indo-Pakistan region, two very well-known and prosperous classes of medical practitioners have demonstrated the efficacy of these herbs in many cases and are still engaged in the preparation of medicines from them in their own special way. In this region, their business in those types of medicine runs into hundreds of thousands of rupees. From the observations of many botanists who visited India in the nineteenth century many important books on these local medicines were written and some of the herbs found their way to the allopathic system of medicines and have been enumerated in the British pharmacopoeia. However, no systematic scientific study of most of these medicinal plants had been undertaken in the past. It is only now that efforts are being directed towards the study of the efficacy of these natural medicines and it is felt very strongly that an institute for the examination of and developmental researches on these plants should be established as early as possible.

It is a matter of consolation that efforts have already been started for the establishment of such an institution in Chittagong (East Pakistan), under the name of the Natural Drug Research and Development Institute. Unesco had shown a good deal of interest in the setting up of such an institute and, three years ago, sent a specialist, Dr. Sandberg, to inspect the region and to present his views on the feasibility of establishing such an institute. A report in this connexion has already been submitted to Unesco but its consideration seems to have been delayed, perhaps temporarily, on the plea that since there are at present so many synthetic drugs produced, there is hardly any necessity for investigations on natural drugs. This view appears to be rather an incomplete appreciation of the present position of the natural drugs. The intention of the said institute is not only to examine the locally available drugs, whose number is quite formidable, but also to undertake work on other similar herbs known in the region extending over the whole of South-East Asia as well as Middle Eastern countries. For work of this gigantic nature, an institute with ample resources is necessary. With the limited resources of Pakistan alone, these efforts can result in only partial success and that also is bound to take a long time. If an international institution such as Unesco could take up this problem as it had earnestly proposed to do in the past, it might be easier to achieve this work with success and in a much shorter time. It is a well-known fact that today quite a number of very important medicines have been

FIG. 5. *Rauwolfia serpentina.*

FIG. 6. *Andrographis paniculata.*

prepared from such plants as *Rauwolfia serpentina* and these have been shown to be superior to many synthetic drugs. This has drawn the attention of chemists and pharmacologists in particular all over the world and a very extensive search has been undertaken among the medicinal plants to discover remedies for diseases such as cancer. It may be mentioned here that even though hundreds and thousands of synthetic preparations have already come out from the various laboratories of many advanced countries, these have not actually supplied the best remedies for many of the human ailments. Even now people who are more alert and who collect information on medicinal plants are induced to look for new medicines from sources which have not yet come to light.

NECESSARY INVESTIGATIONS

It should not be forgotten that in the nineteenth century people knew the plant *Rauwolfia serpentina* (Fig. 5), which grows very well in this region, as an antidote for poisonous bites of animals, and also of snakes. It has also been used for other ailments but more recently the roots of this plant have been found to be very efficacious against hypertension and insanity. Scientific research on *Rauwolfia serpentina* was started in this region in the thirties of the present century; important discoveries were made and the chemical constituents were isolated and studied. However, owing to lack of adequate pharmacological examination at the time, the drug's therapeutic qualities have only recently been made use of on a large scale. Its importance in controlling high blood pressure is well recognized now, and similarly the powder obtained from the whole root is still widely used as a wonder drug in cases of insanity; many lunatics have actually benefited from its use. These new properties of *Rauwolfia serpentina* have come to light only after regular scientific examination of the material was undertaken, when isolation of alkaloids of far-reaching physiological activities were made! There are cases of many other extracts mentioned in the British pharmacopoeia that have been used in the allopathic medicines but there are many more still unknown to the medical world; these, therefore, need a more thorough examination. For these reasons, it is felt necessary that the treasures hidden in the Tibbi and Kaviraji pharmacopoeia are not ignored. They need a very thorough scientific examination which until now could not be undertaken.

In the old literature, the flora of the region has been extensively described but not its pharmacology, and in a few books only have the medicinal properties of many of them been referred to as having been collected from Tibbi and Kaviraji records. The details of the pharmacology of these plants are yet to be studied on modern lines and, therefore, it may not be surprising if some hitherto ill-defined but potent drug is ultimately isolated, which may be effective in cases of very difficult diseases for which the cure is still unknown. In the search for anti-cancer medicines, one plant alone,

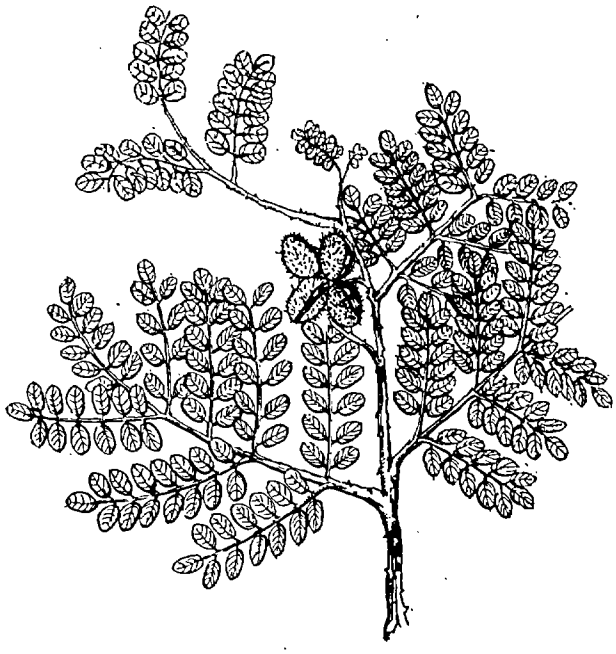

FIG. 7. *Caesalpinia Bonducella.*

FIG. 8. *Acorus calamus.*

namely *Vinca rosa*, was given intensive examination in the recent past. There are many other plants of this region which appear to be potent in many such respects, some for their anti-diabetic action, some as effective in jaundice and many as specifics in asthma, dysentery, tuberculosis and quite a number of other diseases; but these do not appear to have been systematically studied and more interesting features of many of these particular plants may become known when an intensive study of the components of the plants is individually undertaken as happened in the case of *Rauwolfia serpentina.*

PRESENT RESEARCH

Just a cursory look into the list of medicinal plants of the region shows that quite a formidable number of plants are known to have been used as medicines for ages. The users did not know about the chemical nature of the constituents of these plants but they have been dealing with them according to tradition and the earlier study of these was undertaken by inquisitive medical practitioners rather than by chemists and pharmacologists. Consequently, in most cases it is the mixed drug extracts whose physiological activity has been estimated. It is necessary, however, to separate the constituents into pure form before they can produce dependable results. It is with this idea that a systematic effort needs to be started as early as possible regarding their examination and evaluation. The preliminary work that has been undertaken in the East Regional Laboratories, Dacca, has proved to be interesting. Only a brief reference to some of this work can be made here.

From the medicinal chest of the forest growth of this region, only a few samples could be taken out until now. Of these *Andrographis paniculata* (Fig. 6) is a very common household drug; it grows well in East Pakistan and appears to be widely used in children's diseases, including their liver complaints where it produces a very rapid cure. A chemical examination of the plant has yielded some seven chemical products such as andrographolide, andrographane, andrographone, panicolide, etc. One of these is isolated in about 4 per cent yield of the weight of dry leaves. Pharmacological examination of the products is now being carried out.

Caesalpina bonducela (Fig. 7), i.e., the commonly called fever nut, had escaped the attempts of many workers in the past but it has ultimately been possible here to evolve suitable processes to isolate at least three bitter principles, alpha, beta and gamma Caesalpin, together with sugar, some simple proteins and an oil. The last constituent appears to contain a high percentage of a fatty acid which has been shown to be of an anticholesterol type. It can, therefore, be expected that this oil in purified form may be used in cases of hypertension, not only to bring down the pressure temporarily but particularly to remove the very cause of hypertension. The leaves of this plant have yielded about 4 per cent of its weight of a rare

FIG. 9. Jute.

FIG. 10. *Datura strammonium.*

hexahydric alcohol, in the form of its monomethyl ether. It appears to possess the vitamin-like activity of inositol, into which it is converted by a simple chemical treatment. It is expected that this plant will be able to produce the constituents in quantities for their application to human requirements. Perhaps an organized cultivation of the plant would be necessary to assure a constant supply of the constituents.

Acorus calamus (Fig. 8) has yielded quite a good quantity of calomel (about 8 per cent yield), which is itself a good insecticide and produces a stronger insecticide by nitration. In this region good insecticides are necessary for better agriculture and this product promises to be useful in that field.

The effect of humid tropics is very pronounced in some of the plants that grow here very luxuriously. Particular mention of lemon grass can be made. It grows in many places but the vigour and abundance with which it grows in East Pakistan has no comparison. In other climates the plant has been known to give blades of about 22 inches in length whereas in this region the grass leaves grow to the length of 8 feet. The percentage of oil content in these leaves is about the same as in other places. Thus acre for acre yield will be at least four times that of other regions and the leaf blades from which oil has been extracted may be converted with ease and in abundance into cellulosic products such as paper or rayon.

Jute plants (Fig. 9) of the region are definitely superior in quality to jute plants in other regions. It has now been revealed that jute seed can be of great use to humanity. The small quantity of the bitter that is found in it will multiply in quantity if the crop is allowed to yield fruit. The oil produced has the quality of oil obtained from cotton seed and can be used similarly. About 6 per cent of the weight of the seed is raffinose. This suggests that there will be no dearth of this valuable constituent in the world market, when it is produced here in an organized way. While 0.5 per cent of the weight of the seed is strophanthidine, which is itself a strong heart stimulant, the recent efforts suggest that it can be converted into more valuable hormone products, when its importance as a commodity of world demand will increase considerably. Moreover, the leaf bitter is also expected to be an important product which may be useful in the hands of agriculturists as a plant growth hormone.

In the plant kingdom it is expected that similar products will be given by particular plants, growing in different countries although under varying climatic conditions, but some of our work in this region has shown very important variations in the nature and quantities of components present in different plants. Thus *Datura fastuosa* (Fig. 10) of this region has yielded the alkaloid scopolamine, in place of hyoscyamine; and *Cinchona* of this region appears to be rich in quinine content and in addition possesses some new alkaloids which have not yet been identified, but no mention of such alkaloids has been made as regards other varieties of *Cinchona*. The constituents of *Tinospora cordifolia*, as isolated from the herb available here, have been found to be considerably different from

those previously isolated and worked with elsewhere.

Our work on a limited number of these natural medicinal herbs yielded a number of important chemicals the pharmacological examination of which is now going on. The nature of the products obtained appears to be somewhat different from what has been described in the literature. Thus the importance of their pharmacological examination has also developed considerably. The examinations of the various plants lead to the conclusion that the constituents of the plant bodies in humid tropics may show distinct variations in many cases. At present a long and strenuous search is being carried out for an anti-cancer medicine that might be available in some plants. There are a number of plants that have been said to be useful in the cure of cancer; all of these grow within this country. It will, therefore, be possible to undertake the study of a number of such plants and international co-operation would be a very suitable recognition of the importance of work in this field and may lead to better and quicker success.

Some 103 plants are known to have anti-tubercular properties, and anti-dysenteric properties have been attributed to some 188 plants. About 36 plants have been said to be useful in cases of cholera. The antiseptic properties of 240 plants have been mentioned. Some 36 plants are said to have useful effects on prolonged fevers such as enteric fever and there are quite a large number of plants used as remedies for poisonous bites of animals including those of scorpions and snakes. Only after careful scientific investigation can their proper usefulness be assessed and their action on the human system be determined.

Poisonous plants also have long been known and their number is not negligible either; only a scientific examination of these plants can help in the assessment of their activity and utility.

CONCLUSION

These reasons strongly point to the necessity of creating a research organization for the study of natural drugs in this humid tropics region; it should provide a field for international co-operation for the systematic and scientific examination of medicinal plants in general. It is most desirable that an international body such as Unesco should immediately revive its efforts in this direction and provide the intended assistance, particularly since such a measure was strongly recommended by the expert adviser. The government of the country has already supplied its contribution to the effort and it would only be fair that an international body should now play its part so that the benefits accrued by such a research organization in the humid tropical zone could be shared by all countries throughout the world, especially by the different countries of this region.

Résumé

La zone tropicale humide et sa végétation (Muhammad Qudrat-i-Khuda)

L'auteur étudie spécialement la végétation de la zone tropicale humide et insiste en particulier sur l'utilisation des plantes pour l'alimentation et sur leur importance du point de vue économique et médicinal. Les cultures qui permettent de subvenir aux besoins alimentaires de la population de la région comprennent diverses céréales et plantes à tubercules : patates douces, maïs, manioc, qui viennent bien en climat tropical humide. Les fruits comme la banane et l'ananas prospèrent également, et leur production peut être augmentée dans l'intérêt de la population locale. Jacquiers et manguiers trouvent aussi dans cette région des conditions favorables et peuvent fournir un précieux complément à l'alimentation courante. Le *Curcuma zedoary*, qui pousse en sous-bois dans la jungle, promet d'être une source très abondante de fécule qui sera la bienvenue dans les régions actuellement déficitaires en denrées alimentaires.

Parmi les végétaux qui présentent une importance économique, le jute mérite une mention particulière. L'amélioration de la fibre et sa transformation ont été jusqu'ici relativement négligées. Cependant, on a récemment découvert que la tige pouvait servir à fabriquer des plaques ondulées pour la couverture et du bois aggloméré pour la construction; on pourrait aussi en tirer de grandes quantités de papier. Quant aux graines de jute, on pourrait en extraire en abondance une huile, aux propriétés analogues à celles de l'huile de coton. Enfin on peut tirer du jute de grandes quantités de produits comme le raffinose et la strophantine, dont l'emploi est peut-être appelé à se généraliser dans un proche avenir.

La flore des régions tropicales humides comprend des centaines de plantes médicinales diverses dont on ignore généralement la présence et les propriétés. Ces plantes devraient faire l'objet de recherches minutieuses et systématiques, qui seraient utiles au monde entier.

Il est donc souhaitable que l'idée de créer des laboratoires de recherches sur les plantes médicinales et de mise au point de remèdes naturels, conçue par l'Unesco il y a quelque temps, reçoive de cette organisation l'attention bienveillante et le soutien qu'elle

mérite, et cela sans tarder, afin qu'on puisse lui donner suite et accélérer la création de l'institut de Chittagong. Les travaux de cet établissement profiteront à tout l'Extrême-Orient et peut-être au monde entier.

Des recherches sur les plantes médicinales sont certes effectuées dans d'autres parties du monde, mais ces plantes sont si nombreuses dans cette partie du Pakistan qu'il importe de les étudier avec soin. Les laboratoires de recherche que l'on envisage de créer permettront peut-être d'enrichir considérablement la pharmacopée. L'attention des hommes de science a donc été attirée sur ces particularités de la région tropicale humide et sur le parti qu'on en pourrait tirer.

Discussion

SALIMUZZAMAN SIDDIQUI. I would allow myself a brief reference to the therapeutic status of the drugs of natural origin. In a recent authoritative survey of the American pharmaceutical industry, it was brought out that 47.2 per cent of the total number of prescriptions in the United States during 1960 were based on natural products, and 52.8 per cent on synthetic drugs. Out of these 47.2 per cent, however, the antibiotics derived from micro-organisms made for as high a figure as 42.8 per cent leaving a bare 4.4 per cent to physiologically active plant products and their derivatives. We might well ponder over the reasons for this colossal disparity between the role of micro-organisms in the production of therapeutic agents, which have a history of barely two decades, as against that of the medicinal plants with their hoary tradition in the Eastern civilizations. The reason is evident. On quite valid economic grounds, the main objective of scientific studies carried out in the advanced countries of the West has been to emancipate their pharmaceutical industry from its dependence on the plant material resources of the tropics and humid tropics. While a great deal of good has certainly resulted from this trend for the alleviation and prevention of disease, and human welfare, it may yet be stressed that the stepmotherly treatment accorded to the study of drugs of plant origin and insistence on synthetic drugs, with the resulting influx of proprietary medicines in all their baffling kaleidoscopic variations, has in a way been more in the interest of the great drug houses than of the patient.

According to a recent survey hardly 2 per cent of the 191,000 species of flowering plants have been examined for alkaloids, much less other physiologically active constituents.

And so the moral of the whole story is that our chemists, pharmacologists, botanists, and ultimately the clinicians should go all out in a co-operative effort for the study of our medicinal plant wealth, particularly from the tropics, with the set purpose of developing from them new therapeutic agents for the treatment of human ailments on a scientific basis.

B. A. ABEYWICKRAMA. Considering the importance and the urgency of research on the indigenous medicinal plants of the tropics, as pointed out by Dr. Siddiqui, I propose that we make a strong recommendation to Unesco that an Institute for Research on Tropical Drug Plants should be established at a very early date.

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General features of East Pakistan vegetation

Majeed Ahmad

East Pakistan occupies an area of about 54,000 square miles and lies north of the Bay of Bengal. Excepting Cox's Bazar, Chittagong and the Chittagong hill tracts divisions in the south-east and a portion of Sylhet district in the north-east, this province is made up of the flood-plains of the Ganges and Brahmaputra rivers. In this plain the soil varies from pure clay in the tidal flats near the river mouths to a loam. The soil is completely free of stones, and its colour varies from blue-grey to yellow-red. The latter colour is due to the presence of iron oxide. The plain is practically flat, and the maximum variation in elevation is about 100 feet.

The Cox's Bazar, Chittagong and Chittagong hill tracts divisions are a transition between the plains along the Bay of Bengal and the mountainous Lushai hills lying towards the north-east of India. The underlying rocks in this area are chiefly soft sandstone and arenaceous shales. The soil varies from sand to loam in the hills and from loamy clay to clay in the river beds.

East Pakistan lies between latitudes 21° and 27° N. It has on the whole a hot and humid climate. The maximum temperature for the hottest months (April to May) varies from 88° to 100° F. and the minimum for the same months is 73° to 75° F. During the coolest months (December and January) the minimum temperratures range from 45° to 57° F. The rainfall is heavy. It varies from about 68 inches in the Sunderbans to 108 inches in Chittagong and 158 inches in Sylhet.

This province is very thickly populated. According to the 1951 census it has a population of about 41,932,000. Pressure on land is therefore heavy and not much is left for natural vegetation. Approximately 60 per cent of the total area is under cultivation, 16 per cent is forest and the remaining 24 per cent is either fallow or is not cultivated. Of all the zones of vegetation found in the Indo-Pakistan subcontinent, only two are represented in East Pakistan. These are the great Gangetic plain and the eastern salt-water forests which are at their best in the Sunderbans. There are also the hilly tracts of Tippera and Chittagong which, though not included in any particular plant geographic division of the Indo-Pakistan subcontinent, are special forms of the East Pakistan forests yielding the most important forest products.

The forests in East Pakistan lie mainly in Chittagong and the Chittagong hill tracts in the south-east, Sylhet in the north, Dacca and Mymensingh in the centre and Khulna in the south. The rest of East Pakistan includes the great Gangetic plain.

The Gangetic plain is a vast stretch of flatland intersected by rivers, and studded with ponds, *beels*, *haors* and *jheels* (tracts wholly under water for about nine months of the year).

The old river beds, ponds, and *jheels* are all filled with aquatic vegetation. *Eichornia*, the water plant of lower Bengal, is very common and forms a distinctive feature of the landscape. It is our most serious pest and its eradication is proving difficult. Other common aquatic plants are *Euryale ferox*, *Nelumbium*, *Ottelia*, *Vallisneria*, *Potamogeton*, *Ceratophyllum*, *Najas*, *Aldrovanda vesiculosa* (the curious flowering fly trap), *Pistia*, *Lemna* and *Salvinia*. When the river waters overflow during the rains marsh plants, especially Cyperaceae (e.g., *Scirpus articulatus*, *Cyperus rotundus* and *Mariscus microcephalus*), and tall Graminae of many kinds appear (e.g., *Oryza sativa* var. *fatua*, *Coix aquatica* and *Phragmites karka*). In the low-lying areas the common tree is *Barringtonia*.

A few feet above the mean level of the flood, there are fields of rice and jute. The scenery is broken here and there by small villages. *Borassus flabellifer* (Palmyra palm) and *Phoenix sylvestris* are found in the north, central, and western part of the province and *Cocos nucifera* (coconut palm) in the southern areas.

The trees found growing in and around the villages or in barren spaces are *Mangifera indica*, *Ficus religiosa*, *Ficus bengalensis*, *Syzygium cumini*, *Zizyphus mauritiana*, *Borassus flabellifer*, *Cocos nucifera*, *Areca catechu*, *Phoenix sylvestris* and clumps of bamboos and bananas.

The trees that have been introduced into the province are *Polyalthia longifolia*, *Michelia champaca*, *Delonix regia*, *Casuarina equesitifolia*, *Eriodendron anfrasctuosum*, *Salmalia malabarica*, *Artocarpus integra*, *Pterospermum acerifolium* and *Terminalia* spp.

In the plains a variety of weeds is found. *Lantana* has spread everywhere and *Croton sparsiflorus* shows signs of establishing itself in the waste lands. Other common weeds are *Eupatorium odoratum*, *Ageratum conyzoides*, *Mikania scandens*, *Clerodendron infortunatum* and *Evolvulus nummularius*.

The forests of East Pakistan occupy about 8,500 sq. miles distributed in the following five divisions: Sunderbans (2,316 sq. miles), Chittagong hill tracts (4,436 sq. miles), Chittagong-Cox's Bazar (1,048 sq. miles), Dacca-Mymensingh (411 sq. miles), Sylhet (288 sq. miles).

SUNDERBANS

The Sunderbans occupy the southern portion of the Gangetic delta lying above the Bay of Bengal. The soil is clayey and the flat marshy plain is intersected by a network of rivers and channels. The bases of the trees standing on soft mud are alternately inundated with salty brackish water by the tide. These littoral forests derive their name from the tree "sundri", *Heritiera fomes* (H. Minor), which is the chief species.

In general the degree of salinity of the water divides these forests into three zones: the comparatively freshwater area lying to the north-east; the moderately saline area lying east of the Raimangal river; and the salt-water area lying west of the Raimangal river. The quality and density of the forest is best in the freshwater areas to the north-east. The forests become poorer and more open as one proceeds towards the sea or towards the west.

Freshwater areas

In the freshwater areas the predominant species is "sundri". The best "sundri" forest is found on moderately moist land well drained at each ebb tide. "Sundri" is mixed with various quantities of *Excoecaria agallocha* ("gengwā") the proportion of which increases from about 20 per cent in the north and eastern areas to about 50 per cent as one comes to the end of the freshwater areas lying towards the west. Next in importance is *Carapa moluccensis* ("pāssur") mixed with *Brugiera Cylindrica* ("kandra"). Species common on new *chars*, banks of rivers and streams, and *beels* are *Sonneratia apetala* ("keorā"), *Sonneratia acida* ("orā"), *Nipa fructicans* ("golpatta"), and *Avicennia officinalis* ("baen") whose bark is used as a tanning material. It is not known why this palm has been called "golpatta" because the leaves are long and pinnate and not fan shaped as the name suggests. Common species forming the undergrowth beneath the "sundri" are *Cynometra ramiflora* ("singra") on comparatively dry soils and *Amoora cucullata* ("amur") on the moister soils. In the more saline areas the proportion of these two trees is reduced and *Ceriops roxburghi* ("goran") forms the principal undergrowth. The most important weeds of these forests are *Hibiscus tiliaceus* ("bhola"). *Pandanus Odoratissumus* ("kewa kanta"), *Acrostichum aureum* ("hodo" or tiger fern), *Phoenix paludosa* ("hital"), *Acanthus ilicifolius* ("hargosa") and *Brownlowia lanceolata* ("sundri-lota"). "Bhola" has beautiful flowers and the coarse fibres obtained from its bark are used for making cords. "Hargosa" with its blue flowers and spiny leaves forms dense clumps at the intertidal zone.

Moderately saline areas

These areas lie near the sea and around the semi-moribund rivers. "Gengwā" mixed with varying proportions of "sundri" are predominant, but the proportion of "sundri" decreases as one proceeds from north-east to south-west. The "sundri" in these areas is of smaller size. "Passur" occurs in higher proportion in the saline than in the freshwater areas. Towards the more saline areas in the south-west, "keorā", "baen" and "golpatta" become comparatively scarce, and *Rhizophora conjugata* ("garjan") appears.

Aegialitis rotundifolia ("torā") is frequently found near the sea and near banks of larger streams in the west, forming patches of thick jungle.

Salt-water areas

The rivers and *beels* in this area contain saline water throughout the year and the trees are stunted in growth. The forest consists mainly of "gengwā" and "goran", with patches of "hital" growing between them, on the drier soils. The common species on the banks of streams, *khals*, new *chars*, and *beels* are "garjan". *Kandelia rheedei* ("goria"), *Avicennia alba* (white baen "kankra"), *Carapa obovata* ("dhundal") and "pāssur".

Mixed with the mangroves in these forests are members of Typhaceae (*Typha angustata* and *T. elephantica*), Gramineae (*Pasphalum distichum*, *Apluda varia* and *Phragmites karka* var. *Cincta*) and *Cyperaceae* (*Scirpus littoralis* and *Scirpodendron costatum*). It is interesting to note that although grasses are plentiful, no species of bamboo is found in the Sunderbans.

CHITTAGONG HILL TRACTS AND CHITTAGONG-COX'S BAZAR FORESTS

These forests are in a sense transitional between the eastern Himalayan forests in the north and the Burma forests in the east and south. *Shorea robusta* found in the eastern Himalayas does not grow in these areas.

The districts of Chittagong and the Chittagong hill tracts are hilly throughout. Cultivated valleys are sometimes seen and rice and "rabi" crops are grown. Between the hills and the Bay of Bengal is a narrow strip of rice-fields. To the south of these there is a series of flat islands with mangrove formation.

The outstanding feature of these forests is the frequent occurrence of different species of the genera *Dipterocarpus*, *Quercus* and *Eugenia*. The forests are so mixed that it is difficult to classify them. On the whole they can be said to be of the tropical, semi-evergreen type. There is a preponderance of evergreen trees, but these are mixed with a large number of deciduous species. On the north, north-eastern and eastern slopes, in the deep valleys and other localities sheltered from the sun, the forests become more evergreen according to the amount of shade. On the south, south-west and western aspects, according to the degree of exposure, the forests are deciduous. Areas which have been subjected to *jhuming* or shifting cultivation have a very different appearance from areas where the *jhumias* have not penetrated. In the *jhumed* areas there are very few trees but there is a dense undergrowth of *Eupatorium odoratum* ("Assam lota").

The following types of forests are represented in the Chittagong hill tracts and the Chittagong-Cox's Bazar regions but the boundaries between them are not well defined.

Evergreen forests

Tidal forests. Small areas of tidal forests are common in the vicinity of river or tidal creeks. These forests are of the Sunderban type. The freshwater type is not represented at all. *Avicennia officinalis*, *A. tomentosa* and *A. alba* grow everywhere. In the interior *Ceriops roxburghii* forms a dense thicket, and in the low-lying areas *Aegiceras majus* grows abundantly. On the sea front and along the banks of the rivers and on muddy soil *Sonneratia apetala* is most frequent. On higher land and on the river banks which are firm, "sundri" is the main species.

Tropical evergreen forests. These are found in the deep valleys and in localities that are shaded by lofty hills and which have a plentiful water supply. The largest trees are over 100 ft. high, the main species being *Artocarpus chaplasa* ("chapalish"), *Drimycarpus recimosus* ("telsur"), *Sterculia alata* ("narikel"), *Tetramilis nudiflora* ("mainikat"), *Mesua ferrea* ("nagesar"), some *Meliaceae* (e.g., *Dysoxylum procerum* ("dingori"), *Chikrassia tabularis* ("chickrass")), various Lauraceae (e.g., *Dehassia kurzii* ("modon-mosto") and *Phoebe paniculata*), *Eugenia* spp. (e.g., *E. formosa* ("phul jamli") and *E. Operculta* var. *panials* ("paniala jamb")) and *Ficus* spp. (e.g., *F. pomifera*, *F. variegata* and *F. altissima* var. *laccifera*).

Mixed evergreen forests. These forests cover the greater part of the Chittagong and the Chittagong-Cox's Bazar area and they occupy both high ground and the alluvial flats. The tallest trees are usually deciduous and scattered, and range from 80 to 200 ft. in height. The principal species are *Dipterocarpus tubrinatus* ("garjan"), *Buchanania lancifolia* ("civit"), *Salmalia malabarica* ("tula") and *Albizzia procera* ("koroi").

The upper layer of these forests consists of *Dipterocarpus turbinatus*, and *Buchanania lancifolia*, *Salmalia malabarica*, *Albizzia procera*, *Ficus* spp. and *Spondias mangifera*; the second layer includes a large variety of species, the chief being *Sterculia alata*, *Hopea odorata*, *Dichopsis polyantha* ("tali"), *Cedrela toona* ("toon"), *Lagerstroemia speciosa* ("jarul"), *Trewria nudiflora* ("pitali"), *Terminalia belerica* ("bhaira"), *Gmelina arborea* ("gambar"), *Pterospermun acerifolium* ("kanak champa") and *P. semisagittatum*, *Alstonia scholaris* ("chattain"), *Macaranga denticulata* ("burna"), *Quercus* spp. (oaks) (*Q. velutina*, *Q. acuminata*, etc.), *Castanopsis* spp. (*C. castanicarpa*, *C. armata*, etc.) and *Dillenia* spp. (*D. scabrella* and *D. pentagyna*).

Below, there is a third layer of fuel species. In many places seedlings and saplings of the different valuable trees mentioned above cover the ground.

DECIDUOUS FORESTS

Open deciduous forests are seen on the comparatively drier slopes usually with a south to west aspect. The trees are usually scattered, and the principal species found are *Lannea grandis* ("bhadi"), *Albizzia procera*, *Bauhinia malabrica* ("kanchan"), *Steruculia villosa* ("udal"), *Dillenia pentagyna*, *Erythrina indica* *Spondias mangifera* and *Ficus* spp. (*F. pomifera* and *F. roxburghii*, etc.).

There is a considerable variation in the undergrowth of these forests. In less-exposed situations the undergrowth consists of stunted evergreen trees and bamboo. The bamboos occur in scattered patches, the commonest species being *Molucanna bambusaeoides* ("muli"). This is found either pure or mixed with *Bambusa tulda* ("mitenga"). Other varieties of bamboo are *Dendrocalamus longispathus* ("orah") and *Oxytenanthera auriculata* ("kaliserra"). In open situations there is often a dense growth of *Eupatorium odoratum* which occurs alone or mixed with bamboos.

Bamboo jungles

Bamboo jungles can scarcely be regarded as a separate type of forest, as they really form the undergrowth of the different forests. Sometimes, however, they occur in pure blocks, particularly along the eastern slopes of the Kassalong drainage area. They are characterized by the lack of undergrowth. Some of the commonest species are *Molucanna bambusaeoides*, *Bambusa tulda* and *Teinostachyum dullooa* ("dolu").

Savannahs

These are of two types, one of which covers extensive areas where trees have been felled; *Saccharum spontaneum* (sun grass) covers the ground in these areas. The other type is found in swamps or along the edge of streams. It is usually not associated with trees. *Imperata cylindrica* grows both by the edge of streams and swamps.

Dune forests

These are found along the sea-shore. The trees are either evergreen or deciduous, the typical tree is *Casuarina equisetifolia*. Another predominant plant of the sea-shore is the sand-binding *Ipomoea pes-carpae*, which forms the undergrowth.

DACCA-MYMENSINGH FORESTS

These forests lie between the Jammuna and the Brahmaputra rivers and consist of several hundred separate blocks of timber ranging from three to several thousand acres in area. Between these forest blocks are cultivated lands.

This forest is exceptionally pure, *Shorea robusta* ("sal") forming at least 95 per cent of the crop. *Albizzia procera* is often seen associated with *Shorea robusta* while *Dillenia pentagyna* and *Terminalia belerica* occur here and there, and *Eugenia operculata* is found along the edges. In the scanty second layer the commonest species are *Syzygium cumini*, *Miliusa velutina*, *Cassia fistula*, *Holarrhena antidysentrica*, *Careya arborea*, *Flacourtia ramontchi*, *Glochidion velutinum* and *Phoenix acaulis*, while the undergrowth is formed chiefly of *Pennisetum setosum*.

Climbers are large and heavy, the chief being *Spatholobus roxburghii*, *Discorea* spp., *Smilax* spp., *Vitis* spp. and *Ichnocarpus* spp. *Loranthus* is also fairly common and *Eupatorium odoratum is* plentiful in older clearings.

SYLHET FORESTS

These forests are of the mixed evergreen-deciduous type and the flora is more or less the same as the forests described under the Chittagong and the Chittagong hill tracts divisions. One important difference, however, is the presence of "sal" which is found in some parts of Sylhet but not in the Chittagong area. The aggregate forest area is small and occurs in a number of scattered tracts.

The shrub *Clinogyne dichotoma*, the cane *Calamus* spp. and the tea gardens of Sylhet need special mention. *Clinogyne dichotoma* is used for making the famous Sylhet mats, while various varieties of cane have been responsible for the establishment of a flourishing cane industry in the district. In the Sylhet tea gardens, some of the best tea in the world is produced. Tea as one knows is obtained from the shrub *Thea sinensis*.

Résumé

Caractères généraux de la végétation du Pakistan-Oriental (Majeed Ahmad)

Situé entre le 21e et le 27e parallèle nord et couvrant une superficie de 143 000 km², le Pakistan-Oriental comprend les grandes plaines alluviales, les premiers contreforts de l'Himalaya à l'est et une bande de forêts longeant la côte méridionale. Environ 60 % de la superficie totale du pays sont cultivés, 16 % sont occupés par des forêts et le reste (24 %) est en friche.

Les plaines alluviales présentent un paysage de rizières et de champs de jute, parsemé de petits villages. Dans le nord, le centre et l'ouest de la province on trouve ça et là *Borassus flabellifer* et *Phoenix sylvestris*, tandis que dans la partie méridionale *Borassus flabellifer* et *Cocos nucifera* sont très répandus. Les principaux arbres indigènes de la plaine sont *Mangifera indica*, *Ficus spp.*, *Eugenia spp.*, *Zizyphus jujuba* et *Aroca oatochu*. Les espèces communes qui ont été introduites dans la province sont *Artocarpus integra* et *Salmalia malabarica*. *Lantana camara* var. *aculeata*, *Eupatorium odoratum* et *Croton sparsiflorus* sont communs dans les terres en friche; *Eichornia* est une plante aquatique nuisible très répandue

Les forêts occupent environ 20 000 km², répartis dans cinq régions : Sunderbans, Chittagong Hill Tracts, Chittagong Cox's Bazaar, Sylhet et Dacca-Mymensingh.

La région des Sunderbans, qui longe le golfe du Bengale, a une végétation d'estuaire : forêts denses à feuilles persistantes et mangroves. Les espèces typiques sont *Heritiera*, *Excoecaria*, *Brugiera*, *Carapa*, *Rhizophora*, *Sonneratia* et *Avicennia*, auxquelles il faut ajouter deux plantes grégaires : *Nipa Fruticans* et *Phoenix paludosa*.

Les forêts des Chittagong Hill Tracts et de Chittagong Cox's Bazaar comprennent cinq catégories : feuilles persistantes, feuilles caduques, jungle de bambous, savane et forêts de dunes. Les forêts à feuilles persistantes se subdivisent en : *a*) forêts maritimes, du type Sunderbans; *b*) forêts tropicales à feuilles persistantes, dans les vallées profondes et humides, les principales espèces étant *Artocarpus*, *Hopea*, *Tetrameles*, *Amoora*,

et *Cedreala; c*) forêts mixtes à feuilles persistantes où les principales espèces sont *Dipterocarpus*, *Buchanania*, *Salmalia* et *Albizzia*.

Les forêts à feuilles caduques se trouvent sur les pentes découvertes et relativement sèches; les principales espèces sont *Dipterocarpus*, *Lannea*, *Pterygota*, *Dillenia* et *Erythrina*. Les jungles de bambou forment des masses compactes ou sont parsemées dans les régions de forêts à feuilles persistantes et de forêts mixtes (sempervirens et caducifoliées). Les variétés les plus courantes sont : *Melocanna*, *Bambusa*, *Oxytenanthera* et *Teinostachyum*. Les savanes sont peuplées en abondance de *Saccharum spontaneum* et *Imperata cylindrica;* dans les forêts de dunes, qui longent la côte, l'espèce principale est *Casuarina equisetifolia*.

Les forêts de la région de Dacca-Mymensingh sont des formations presque pures de *Shorea robusta*, tandis que les forêts de la région de Sylhet sont du même type mixte—feuilles persistantes, feuilles caduques—que dans la région de Chittagong, la seule différence étant la présence occasionnelle, ici, de *Shorea robusta*.

Discussion

M. Schmid. *Quercus* is a temperate plant. What are the elevations at which it is found in East Pakistan?

M. Ahmad. It is found at altitudes between 1,000 and 3,000 ft. in the Chittagong hill tracts. The maximum height of the Chittagong hill tracts is about 3,000 ft.

H. Brammer. If man had not cut down the vegetation, what would be the climatic climax in East Pakistan?

M. Ahmad. There would have been mostly mixed evergreen forests; the evergreen trees predominating in moist areas and the deciduous trees becoming abundant in drier localities.

S. Siddiqui. Has any pollen analysis from peat deposits been undertaken to determine the type of plants responsible for the formation of peat deposits?

M. Ahmad. No research work has been undertaken on this problem.

H. Brammer. (1) Does Professor Ahmad have any evidence of what might have been the natural vegetation covering the flood-plain areas of East Pakistan before this was cleared for cultivation by man?

(2) In many soils in East Pakistan we find buried organic layers. Does Professor Ahmad know if the species whose remains are found in these layers have been identified and whether work has been done on pollen analysis in these layers?

M. Ahmad. As far as the first question is concerned, there are indications that grasses and reeds formed the main vegetation, together with some trees such as "sal". Little ecological work has been carried out in this direction, however. In reply to the second question, no pollen analysis has been carried out.

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The estuarine vegetation of Ceylon

B. A. Abeywickrama

The island of Ceylon is situated to the south of the Indian peninsula and lies between latitudes 5° 55′ and 9° 51 N. and longitudes 79° 42′ and 81° 52′ E. It has a total area of 25,332 sq. miles. It is roughly pear-shaped and the maximum length and breadth are approximately 270 miles and 140 miles respectively. A narrow strip of shallow sea separates the island from the mainland. The land area is composed largely of very ancient crystalline and metamorphic rocks. The south-central part is mountainous and has an elevation ranging from 3,000 to about 8,000 ft. This region is surrounded by an upland belt 1,000 to 3,000 ft. high. The coastal region forms a plain which is most extensive on the northern and eastern sides. Ceylon lies on the same continental shelf as peninsular India, and the 100-fathom marine contour line lies very close to the coast except on the north-west where the continental shelf stretches far out and joins that of the Indian subcontinent.

The average temperature in the lowlands is about 80° F. In the wet zone, i.e., the south-western plains and the central highlands, the rainfall ranges from 75 to 200 inches per annum and is somewhat evenly distributed through the year. In the northern and eastern plains the rainfall is seasonal and there is a prolonged drought period. The major part of this region receives annually about 50 to 75 inches of rain and is referred to locally as the dry zone. The extreme north-west and the south-east, which are referred to as the arid zones, receive only 25 to 50 inches of rain per annum, and that too is seasonal.

The rivers rise in the central hills and radiate out towards the coast. The discharges from these rivers show wide differences. For each square mile of catchment area the annual discharge from rivers in the wet zone ranges from 1,000 to about 5,000 acre ft., whilst that from the rivers in the dry zone and arid zones ranges from only 125 to 1,000 acre ft. Farther in the wet zone the discharge is fairly evenly distributed through the year but in the dry and arid zones the discharge is seasonal and some of the rivers in this region run dry during the drought periods (Caine, 1952).

The heavy rains cause a considerable amount of erosion in the central highlands and the river water often carries a fair amount of mineral matter in suspension. A part of this mineral matter is deposited in the estuaries to form alluvial soils or mud flats. At the same time beach material—sand, etc.—thrown from the sea often accumulates near the river mouths to form sand bars. In this manner many river mouths have become blocked by mud flats and/or sand bars and behind them numerous shallow coastal lagoons have formed.

The coasts of the island are constantly laved by monsoon currents. Of these the more powerful currents occur during the south-west monsoon period, i.e., from about May to August, and these affect mainly the south-western coastal region. Because of the presence of very deep seas round the major part of the island the influence of the tides is very small. Along the southern shores the daily tidal range is often only a few inches. The range of high spring tides varies from 2 ft. to 2.6 ft. and the highest tides ever recorded have never exceeded 4 ft. (Cook, 1931).

VEGETATION

The types of vegetation found in the estuarine areas are determined mainly by the salinity and depth of the ground water, the nature and the stability of the substratum, and the frequency and the extent of the tidal immersion. As these factors vary gradually with changes in the relative levels of land and sea, and with the increase in the distance of the land from the sea, the estuarine floras exhibit a very marked zonation.

In the estuarine areas in Ceylon the following vegetation types can be recognized: the mangrove vegetation, the freshwater-marsh vegetation, and the salt-marsh vegetation.

The mangrove vegetation

The mangrove vegetation is very poorly developed in Ceylon when compared to that in India, Malaysia and Indonesia. In the past the mangroves seem to have occupied a much greater area than they do at present. Tennant (1859) describing the local vegetation about a century ago says that a dense growth of mangroves occupied the shores of the island. Evidence from old maps and place-names confirms this statement. Most of these areas have now been drained for cultivation or building purposes and mangroves are at the present time restricted to relatively small areas. They extend to the sea front only in the Mannar region where the continental shelf spreads far out and the seas are shallow and calm. Elsewhere they are confined to river estuaries, shallow coastal lagoons and the shores of the deeper lagoons.

The mangrove species establish themselves on intertidal mud flats or humic sands in places where the substratum is not much disturbed by wave action. The plants do not initiate soil deposition. They only colonize areas where alluvium is already present but when they are once established they accelerate the soil-building processes.

The mangrove forests have a relatively small number of plant species when compared with other forest communities in Ceylon. This total number of mangrove species is only about 28. All these have wide distributions and none of them is endemic to the island (Abeywickrama, 1956).

The genera *Rhizophora*, *Bruguiera*, *Avicennia* and *Sonneratia* form the great bulk of the local mangroves, (Abeywickrama, 1960; Chapman, 1947; Tansley and Fritsch, 1905). Where the river banks or the shores of the lagoons have steep slopes *Rhizophora mucronata* or *Rhizophora apiculata* form a fringe near the water's edge. With their numerous, characteristic prop roots these two species can invade even deep waters and in certain localities they form extensive pure stands. Behind them on the landward side there is a mixed mangrove with *Bruguiera gymnorhiza*, *Sonneratia caseolaris*, *Avicennia officinalis*, *A. marina*, *Ceriops tagal*, *Aegiceras corniculatum*, *Lumnitzera racemosa*, *Acanthus ilicifolius* and *Acrostichum aureum*. *Bruguiera sexangula*, *Bruguiera cylindrica*, *Ceriops decandra*, *Scyphiphora hydrophyllacea* and *Lumnitzera coccinea* may also be present in the mixed mangrove but these are somewhat rare. Among their common associates are *Excoecaria agallocha*, *Dolichandrone spathacea* and *Annona glabra*. On the higher ground behind the mangrove proper these plants become associated with littoral woodland species, e.g., *Terminalia catappa*, *Calophyllum inophyllum*, *Heritiera littoralis*, *Cerbera manghas*, *Tamarix gallica* and *Clerodendrum inerme*. In this region the ground layer often has several species normally found on sandy sea-shores, e.g., *Ipomoea pescaprae*, *Phyla nodiflora*, *Canavalia rosea*, *Agyneia bacciformis* and *Tephrosia purpurea*. Epiphytes are almost absent except for a few Loranthaceae which grow as partial-parasites and certain lichens, e.g., *Roccella* spp. which grow on the trunks of the larger trees. Lianas, e.g., *Derris uliginosa*, *Dalbergia candenatensis*, etc., however, are often present.

Where the shores or the river banks have more gentle slopes *Avicennia officinalis*, *A. marina*, *Sonneratia caseolaris* or *Acanthus ilicifolius* may extend right up to the water's edge. Of these *Sonneratia* and *Acanthus* appear to be less tolerant towards high salinities than *Avicennia*. In the mangrove communities north of Mannar, *Avicennia* spp. dominate the vegetation on the sea front (Chapman, 1947). *Sonneratia caseolaris* is often a pioner in mud flats in river estuaries and this species sometimes occurs several miles inland where the water has a very low salinity almost approaching that of fresh water. In mud flats in the Negombo lagoon and near the Bentota river the earliest phanerogamic colonizer is usually *Acanthus ilicifolius*. This may then cover the entire surface of some small islands forming almost pure stands. Later *Bruguiera* spp., *Aegiceras corniculatum*, etc., invade these islands and form mixed mangroves.

Along the south-western coastal areas the river estuaries and the shores of certain lagoons have a fringe of *Nipa fruticans*. This appears to be less tolerant towards salinity than even the mixed mangrove and is absent from the northern and eastern coasts where the salinity in lagoons, etc., often rises well above that of sea water during the dry season.

The total distance which the true mangroves extend inland up the rivers is variable. In some cases the mangroves are confined to the near vicinities of the river mouths whilst in others they extend a few miles inland. These differences seem to be correlated to differences in the amount of water discharged by the various rivers. When the discharge of water is high and is evenly distributed through the year, e.g., the Kelaniganga which has a discharge of 4.956 million acre ft., and the Kaluganga with one of 5.88 million acre ft., the brackish water zone is confined to the immediate neighbourhood of the river mouth and the mangroves are restricted to this zone. On the other hand in rivers where the annual discharge is low, e.g., the Maduganga with a discharge of 0.046 million acre ft., or the Bentotaganga with one of 0.850 million acre ft., the influence of the sea water extends far inland and as a result the mangroves themselves have a correspondingly wider distribution.

THE FRESHWATER-SWAMP VEGETATION

With increasing distance away from the sea as the brackish water is gradually replaced by fresh water, more and more freshwater species replace the mangrove species and where marshy conditions occur on the river banks the mangrove gives way to a freshwater-swamp vegetation.

A belt of *Hanguana malayana*, *Phragmites karka*, *Lagenandra* spp., or *Erianthus arundinaceus*, often separates the running water from the surrounding marshes and shallow pools. Among the former a few mangrove plants, e.g., *Sonneratia caseolaris*, may sometimes be present. The marsh vegetation generally consists of various sedges, grasses, aroids, *Calamus* spp., *Eriocaulon* spp., *Xyris* spp., *Typha angustifolia*, *Limnophyton obtusifolium*, *Flagellaria indica*, *Monochoria* spp., *Nepenthes distillatoria*, *Drosera* spp., *Utricularia* spp., etc. In addition woody species, e.g., *Hibiscus tibiaceus*, *Pandanus zeylanicus*, *Cerbera manghas*, *Syzygium* spp., *Ardisia* spp. are often present. In the pools *Nelumbo nucifera*, *Nymphaea* spp., *Nymphoides* spp., *Aponogetan* spp., *Ceratophyllum demersum*, *Myriophyllum indicum* and *Utricularia* spp., are found. One of the commonest plants in the swamps in the backwaters in the wetter parts of Ceylon is *Salvinia auriculata*, which has now become a serious pest.

The salt-marsh vegetation

The salt-marsh vegetation in Ceylon is confined to the coastal areas of the arid regions mainly in the south-western and north-eastern parts of the island. The rivers and streams in these areas have a very low and seasonal discharge. Some estuarine lagoons and mud flats get separated from the sea by sand bars during the dry seasons. The water in them evaporates and in some of them free salt crystallizes out. In such habitats *Avicennia* is often the only mangrove plant and the vegetation is dominated by true halophytes. In the salt marsh on the shores of Lake Mundel, Chapman (1947) has recorded the following vegetation zones : (a) a rush zone with *Cyperus haspan* and *Scirpus littoralis*; (b) a *Zoysia matrella* consociation with occasional trees of *Avicennia* spp. or *Heritiera littoralis*; (c) open ground with bushes of *Suaeda monoica* and some *Zoysia matrella* and *Eleocharis setacea*; (d) open ground with *S. monoica* and occasional *Z. matrella* and *Arthrocnemum indicum*; (e) bare mud with patches of blue-green algae; (f) zone of *Halophiea ovalis*, leading to (g) mangrove swamp dominated by *Avicennia* spp.

ECONOMIC IMPORTANCE

In Ceylon the mangrove species are of relatively little economic importance. The larger trees and shrubs yield a certain amount of timber and firewood. The genera *Rhizophora*, *Bruguiera* and *Ceriops* provide tannin. *Bruguiera* is also said to yield a black dye (Lewis, 1934). The fruits of *Sonneratia caseolaris* are eaten and the pneumatophores of this plant are used as a substitute for cork.

The mangrove vegetation as a whole accelerates the soil-building processes by assisting the deposition of mineral and organic matter and by arresting erosion due to tidal action or waves. In some localities, as at Muturajawela, the accumulation of humus, which seems to have originated largely from the mangrove vegetation itself, has resulted in the formation of rather extensive peat deposits. The land that has been consolidated by the action of the mangrove plants has been put to various uses by man. In Ceylon most of the mangrove land has been drained and is now used for cultivation of crop plants, especially coconuts.

The freshwater swamps have in most places been converted into paddy fields. The vegetation in the swamps is by itself of little economic use except for the fact that certain sedges are used for making mats, etc. The salt marshes occupy only a very small area in the island and up to now they have not been put to much use.

Résumé

La végétation des estuaires de Ceylan (B. A. Abeywickrama)

Dans les estuaires de Ceylan, on peut distinguer les types de végétation suivants : *a*) mangrove; *b*) végétation des marais d'eau douce; *c*) végétation des marais salés. Le type de végétation et l'aire qu'il occupe dépendent dans une large mesure de la topographie du terrain, ainsi que du volume et de la répartition saisonnière des apports des fleuves.

La mangrove cingalaise se caractérise surtout par la prédominance d'espèces des genres *Rhizophora*, *Bruguiera*, *Avicennia* et *Sonneratia*. *Nipa* ne se rencontre que dans les régions littorales du sud-ouest : on ne le trouve pas sur les côtes à saison sèche du nord et de l'est.

A mesure que l'on pénètre à l'intérieur des terres et que la salinité de l'eau diminue, la mangrove cède peu à peu la place à la végétation des marais d'eau douce. Aux extrémités nord-ouest et sud-est de l'île, les plantes de la mangrove deviennent chétives et sont remplacées par une végétation de marais salé.

La végétation des estuaires de Ceylan a été défrichée sur de grandes étendues, et le terrain a été drainé pour être mis en culture.

Discussion

S. SIDDIQUI. Are *Anacardium occidentale* and *Semecarpus* found in the mangrove forests of Ceylon?

B. A. ABEYWICKRAMA. These are not found in the mangrove forests. *Anacardium occidentale* is a tropical American plant which has been introduced to other parts of the Tropics. In Ceylon it has now become naturalized and is common in some of the wastelands in the low country. We have several species of *Semecarpus* in Ceylon. They are found in the wet evergreen forests.

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The estuaries of the Amazon and Oiapoque rivers and their floras

J. Murça Pires

ESTUARY OF THE AMAZON

Introduction

The Amazon region is an enormous area of about 6 million sq. km., of which more than half (3.5 million sq. km.) is situated in Brazil. It is almost completely covered by a tall, equatorial, virgin forest.

Its area corresponds almost exactly to that of the basin of the Amazon, but in order to embrace areas with the same flora it is necessary to include the basins of some smaller rivers that drain directly into the Atlantic, such as those in Maranhão to the east of the mouth of the Amazon, and those in Amapá and the Guianas to the north. To these must be added the headwaters of the Orinoco basin. The Amazon region then, in the south and south-east, abuts on the Central Brazilian Plateau, on the east with the area of transition along 44°W., on the west with the foothills of the Andes, and on the north with the upper Orinoco region in Venezuela and with the Atlantic. The region can be clearly seen on a map of South America by observing the limits of the basins of the included rivers.

To the south and south-east of Amazonia, on the Central Brazilian Plateau, occur *campos cerrados*, or savannahs. The streams that drain these savannahs are fringed by gallery forests. Elements of the Amazonian *várzea* forests (i.e., forests that are annually flooded) occur in these gallery forests, penetrating into the savannahs sometimes more than 500 km. This gives rise to the curious fact that, in the middle of the savannah region, native rubber trees are being tapped in the gallery forests.

Because of its geological history, water and altitude are important factors in characterizing Amazonia. According to present ideas, the Amazon region was originally a mediterranean sea between the Guiana and Central Brazilian massifs. Afterwards the rise of the Andes and other areas that occurred caused much erosion and sedimentation. Amazonia, therefore, is mostly a plain situated between 0 and 200 metres altitude. The Amazon falls only 2 cm. per km. Its current is caused by the pressure of its volume of water, being little influenced by the incline of its bed.

It is customary to divide the Amazon into three parts: the upper Amazon, the lower Amazon and the estuary.

Upper Amazon

Also known as the Solimões river in Brazil and the Marañon river in Peru, it is the part from the headwaters to the entrance of the Rio Negro. The alluvial plain of this portion in Brazil measures 15,000 sq. km. (Gourou, 1950). It is covered mainly by a tall forest much more vigorous than the gallery forests in the lower course.

The alluvial or annually flooded plains in Amazonia are called *várzeas*, They vary up to 50 km. wide, especially where the *várzeas* of more than one river coalesce. The largest trees in the *várzea* forests of the Solimões are *Olmediophaena maxima* Ducke, *Hura crepitans* L., *Ceiba pentandra* Gaertn. and several species of *Ficus*. The upper Amazon does not feel the effects of the tides; flooding is caused only by the annual rains.

Lower Amazon

This is the portion between the mouth of the Rio Negro and the mouth of the Xingu. Its *várzea* terrain measures 15,000 sq. km. (Gourou, 1950). In the lower part there is a small tidal influence but, as in the Solimões, the floodings are caused by the annual rains and last several months. The river plains contain extensive areas of annually flooded, treeless fields called *campos de várzea*, covered almost exclusively by robust grasses called generically *Canarana*. This name indicates its similarity to sugar-cane and includes *Paspalum fasciculatum* Willd., *P. repens* Berg, *Hymenachne*

amplexicaulis (Rudge) Nees, *H. donacifolia* (Raddi) Chase, *Echinochloa polystachya* (HBK.) Hitchc., *Panicum aquaticum* Poir., *P. elephantipes* Nees, *P. zizanioides* HBK., *Leersia hexandra* Sw., *Luziola spruceana* Bth., *Eriochloa punctata* (L.) Desv., and some species of wild rice, *Oryza alta* Swallen, *O. latifolia* Desv., *O. perennis* Moench. and *O. grandiglumis* (Doell) Prod. (Black, 1950).

In the middle of these grassy *campos* lakes commonly occur which vary in size with the season. During the dry period they contract, the banks becoming occupied by the *Canarana*.

The gallery forests occur principally on levees along the shore of the main river, formed by the deposition of the heavier soil particles during the flood periods. Behind them the *campos de várzea* with their lakes are always found. The levee forests are not very wide, only 200 metres on the average. Among their tallest trees are *Hura crepitans*, *Calycophyllum spruceanum* Bth., *Ceiba pentandra.*, *Triplaris surinamensis* Cham, etc. An interesting fact is the absence of palms.

Economically, the *campos de várzea* are very favourable habitats for raising cattle, particularly water buffaloes. Artificial pastures on the uplands (*terra firme*) are needed for them during the months of flood. At present these do not exist in the region because of the primitive methods of the inhabitants.

In these levee gallery forests Japanese immigrants are growing jute, the fibre used for sacks.

The Amazon estuary

After giving the above as an introduction, we come to the estuary usually defined on the Amazon as the part between the mouth of the Xingu and the Atlantic (see Fig. 1). According to Gourou (1950) the area of its alluvial plain is 25,000 sq. km.

In the upper part of the Amazon, as stated, the floodings are caused by the annual rains, but as one approaches the ocean, the river bed becomes so wide that the rains lose their effect in causing the floodings. In the estuary floodings are caused by the tides. In March-April and in September the tidal floodings in the lower estuary are strongest. Thus the September flood occurs in the middle of the dry season which runs from June to December.

The enlarging of the river bed at its mouth causes a reduction in the flow velocity of the stream. This, plus the effect of the tides, causes the deposited sediments to form hundreds of islands connected by an intricate network of canals. For this reason the upper part of the estuary is called "Region of the Islands". The canals are locally called *furos*, the larger ones being called *paranás*.

The estuary is of fresh water. Near the ocean it can become slightly brackish at certain times of the year.

The highest tides are from 3 to 4 metres. In some places a phenomenon called the *pororoca* occurs; it consists of two or three consecutive waves travelling upstream, which in shallow places break and form a surf. The *pororoca* is the beginning of the tidal flooding which occurs twice daily.

The Amazon empties into the ocean by way of two rivers, one on each side of the island of Marajó. This island has an area of more than 40,000 sq. km. Almost all of the volume of water of the Amazon enters the northern branch, between Marajó and Amapá. Only a small fraction enters the southern branch; along with the water of the Tocantins, Moju, Acará and Guamá rivers, they form the so-called Pará river and the Bay of Guajará.

When the muddy water of the Amazon empties into the sea, it is pushed by an ocean current towards the coast of Amapá and the Guianas. The mud is deposited along the coast forming bars across the river mouths, obstructing navigation. For this reason also sandy beaches in the region are found only east of the mouth of the Amazon.

Vegetation of the Amazon estuary

As previously stated, the alluvial plain of the upper Amazon supports *várzea* forests. In the lower Amazon *várzea* forests are less important on the inundated terrain, the tall, grassy *campos de várzea* being much more extensive.

In the estuary these *campos de várzea* do not occur. On the older islands important vegetation types are found, rich in tree species and valuable as timber sources.

In this "Region of the Islands" the main sawmills of the State of Pará are located, and both sawn lumber and logs come from it.

Timber from the *várzea* forests and the adjacent upland forests is transported by water, the logs being made into rafts.

The *várzea* forests of the estuary contain an abundance of palms and these strongly influence the physiognomy of the vegetation. The most common species are *Euterpe oleracea* Mart. ("açaí"), *Mauritia flexuosa* L. f. ("buriri"), *Raphia taedigera* Mart. ("jupati"), *Manicaria saccifera* Gaertn. ("ubuçu"), *Iriartea exorrhiza* Mart. ("pachíuba"), *Astrocaryum murumuru* Mart. ("murumuru"), etc.

The principal vegetation types of the estuary are forests, *furos* vegetation, *campos* and mangrove swamps.

Estuary forests

Since the area of these forests is so large it is difficult to give a general description. We prefer to give data about two particular places. Breves in the south or Marajó Island, and Belém, further down river and neaf the ocean.

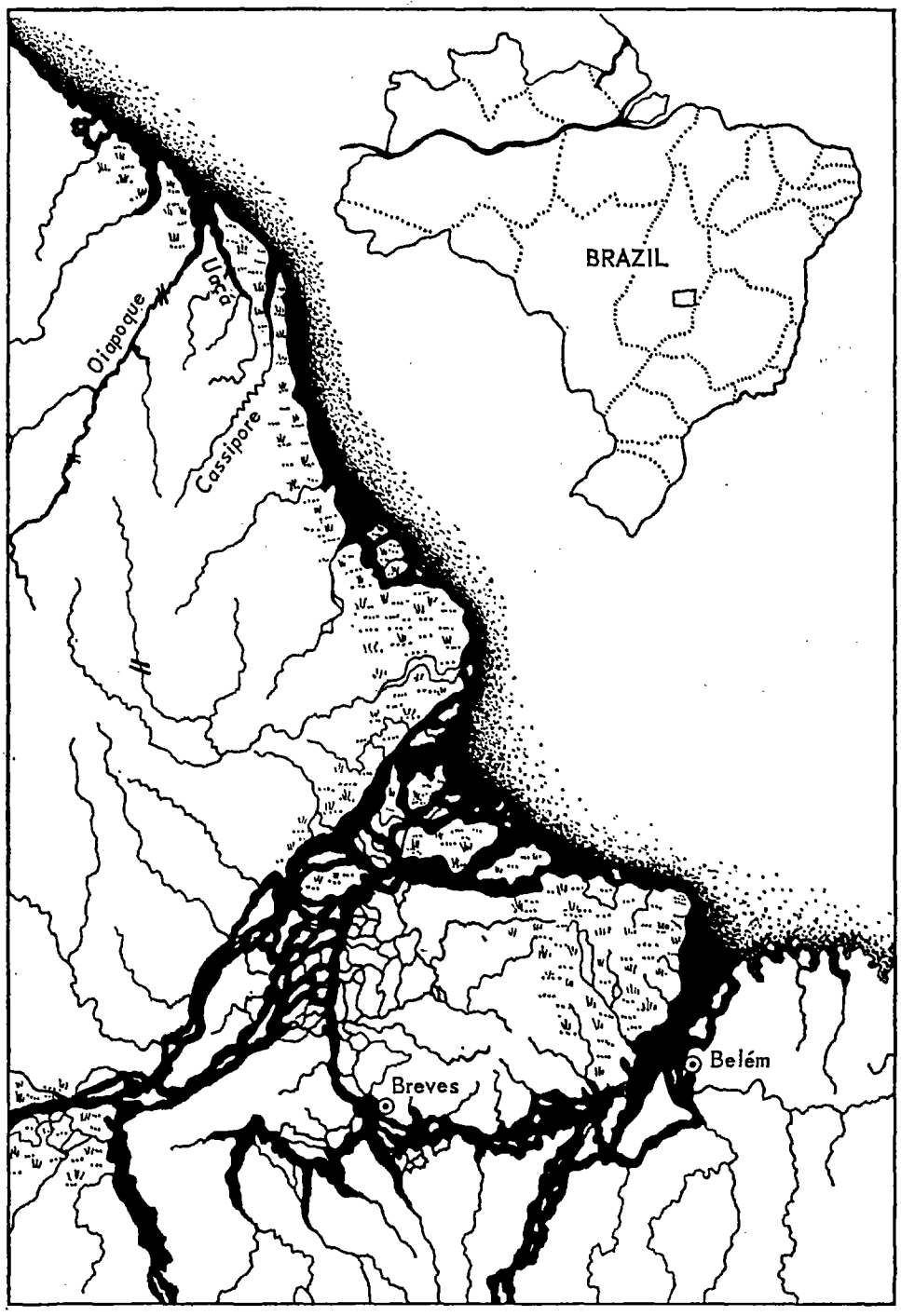

FIG. 1. Map showing the estuaries of the Amazon and Oiapoque.

Estuary forest in Breves. In 1956 we spent a month in this locality, obtaining data as yet unpublished. These will be partly presented here to give an idea of the forest. We were accompanied by two soil specialists who published independently their soil data (Vieira and Santos, 1962).

The vegetation we studied was partly in a terrain whose soil becomes periodically somewhat soaked, and partly in upland *terra firme* whose water table comes almost to the surface in the rainy season.

Data for 1 hectare of a transect. All plants with trunks 10 cm. in diameter or more were counted; 516 individuals in 157 species in 36 families were encountered. The most common species were: *Iryanthera paraensis* Huber (5.62 per cent of the total), *Protium* sp. (5.23 per cent), *Eschweilera corrugata* (Poit.) Miers (4.84 per cent), *Protium spruceanum* Engl. (3.88 per cent), *Licania* sp. (2.52 per cent), *Chrysophyllum prieuri* A. DC. (2.33 per cent), *Tovonita* sp. (1.94 per cent); *Aspidosperma album* (Vahl) Ducke (1.74 per cent), *Aniba burchelli* Kosterman (1.74 per cent); *Gilibertia* sp. (1.74 per cent). These 10 most common species make up only 31.6 per cent of the total number of individuals, showing how rich in species this vegetation is, with a consequent small number of individuals per species.

The frequency in trunk diameter classes was: 10-20 cm.; 308 individuals; 20-40 cm., 110 individuals; above 40 cm., 98 individuals.

Data for 10 hectares of a transect. The transect here was 10 by 10,000 metres; individuals were counted only when they had a trunk diameter of 25 cm. or more at 1.5 metres from the ground, and the volume of wood in the trunk from ground level to the lowest bough was also calculated: 1,271 individuals were counted, in 235 species, in 40 families.

The 10 most common species were: *Eschweilera corrugata* (6.22 per cent), *Taralea oppositifolia* Aubl. (5.90 per cent), *Vouacapoua americana* Aubl. (3.54 per cent), *Eschweilera odora* (Poepp) Miers (3.46 per cent), *Pentaclethra macroloba* (Willd.) Kuntz (2.60 per cent), *Macrolobium brevense* Ducke (2.60 per cent), *Licania macrophylla* Bth. (2.12 per cent), *Licania* sp. (1.57 per cent), another *Licania* sp. (1.57 per cent), *Vochysia inundata* (1.57 per cent). Only 31.15 per cent of the individuals were included in these 10 species.

The 235 species yielded 2,131.30 cu. metres of wood, or 212.13 cu. metres per hectare, or 0.65 cu. metre per species, on the average.

The 10 species with the greatest wood volume were: *Taralea oppositifolia* (6.3 per cent of the total), *Vouacapoua americana* (4.9 per cent), *Eschweilera corrugata* (3.7 per cent), *E. odora* (3.4 per cent), *Vochysia inundata* (3 per cent), *Goupia glabra* Aubl. (3 per cent); *Cedrelinga catenaeformis* Ducke (2.6 per cent), *Osteophloeum platyspermum* Warb (2.4 per cent), *Caryocar microcarpum* (2.4 per cent), *Saccoglottis cuspidata* Bth. (2 per cent). These 10 species gave 33 per cent of the total wood volume.

Thus, timber production also involves many species, without predominance of any one or few. This is a problem in exploitation, particularly as regards standardization.

The tallest tree encountered was an individual of *Dinizia excelsa* of 41 metres. Eleven species had individuals over 30 metres tall (two of these emergents are *Cedrelinga catenaeformis* and *Dinizia excelsa*), 176 species had individuals between 20 and 30 metres tall, and 48 species had individuals between 8 and 20 metres tall.

The basal area of the trunks of the counted species was 20.18 cu. metres per hectare. The 10 species with the largest basal area were: *Taralea oppositifolia* (8.12 per cent of the total basal area), *Voucapoua americana* (4.62 per cent), *Eschweilera corrugata* (3.88 per cent), *E. odora* (2.39 per cent), *Goupia glabra* (2.83 per cent), *Vochysia inundata* (2.42 per cent), *Osteophloeum platyspermum* (2.42 per cent), *Caryocar microcarpum* (2.25 per cent), *Pentaclethra macroloba* (2.17 per cent), *Licania macrophylla* (2.03 per cent).

Data for 1 hectare of cut trees. On 1 hectare all trees with trunks over 10 cm. in diameter were cut at about ground level. The hectare was made up of four plots of 1/4 hectare each, distributed along a line 5 km. long. The thick trunks (25 cm. and over) were measured with tape directly to calculate their volume. Thin trunks and cut boughs to about 5 cm. diameter were piled up and the volume of the pile measured, applying a correction factor previously worked out to obtain the volume of pure wood.

A total of 402 individuals were counted in 155 species in 35 families. The total volume of trunks alone, 25 cm. and over in diameter, was 331 cu. metres; that of these trunks plus boughs and thin trunks was 455 cu. metres.

The 10 species giving the greatest amount of wood were as follows (in each case with the volume of cubic metres of thick trunks followed by the volume of trunks plus boughs): *Chrysophyllum oppositum* Ducke (24.03, 34.30), *Dinizia excelsa* Ducke (23.88, 28.79), *Tachigalea myrmecophila* Ducke (9.03, 9.05), *Vouacapoua americana* (13.30, 17.33), *Pouteria engleri* (14.04, 17.27), *Osteophloeum platyspermum* (13.23, 14.74), *Macrolobium brevense* (8.91, 12.86), *M. campestre* (7.77, 12.28), *Pithecelobium pedicellare* (6.07, 9.43), *Taralea oppostitifolia* (6.48, 9.18).

Várzea forest in Belém (Plates V and VI). The following information is extracted from a previous paper (Pires and Koury, 1959).

Data for 1 hectare of cut trees. The hectare was made up of four plots of $^1/_4$ hectare each, distributed at random within a small area. All woody plants with trunks of 5 cm. and over were cut at about ground level and the volume of wood measured as described above.

Total volume of thick trunks was 236.26 cu. metres, total volume of wood 433.80 cu. metres; 539 individuals in 53 species in 21 families were counted.

Species with the greatest number of individuals were: *Astrocaryum murumuru*, 152; *Euterpe oleracea*, 113 (counting each clump of several stems as one individual); *Carapa guianensis*, 19; *Bactris* sp., 17; *Quararibea guianensis*, 15; *Hevea brasiliensis*, 13; *Inga cinnamomea* Bth., 13; *Hura crepitans*, 12; *Guazuma ulmifolia* Lam., 12.

Data from 3.8 hectares. In the same area a plot was laid out 100 metres wide, running perpendicular from the edge of the Rio Guamá 380 metres to *terra firme*. Of woody plants with trunks 10 cm. in diameter and more, there were 1,837 individuals in 107 species in 33 families. There were 1,133 individuals with trunks from 10 to 20 cm. in diameter, 375 with trunks 20 to 40 cm. in diameter, and 329 with trunks more than 40 cm. in diameter.

The 10 most common species were *Euterpe oleracea*, *Astrocaryum murumuru*, *Pithecelobium latifolium* (L.) Bth., *Carapa guianensis*, *Quararibea guianensis*, *Hura crepitans*, *Pentaclethra macroloba*, *Hevea brasiliensis*, *Inga nobilis* Willd. and *Protium heptaphyllum* March. For further details consult Pires and Koury (1959), Cain *et al.* (1956) and Black *et al.* (1950).

Vegetation of furos, *river banks and recently formed islands.* The forests of Breves described above occupy the higher *várzeas* and also some areas of terrain not flooded but whose water table comes almost to the surface during the rainy season. The terrain to be discussed now, also at Breves, is always very muddy and clayey. It has a uniform flora that is not very rich in species and which is the same in the whole estuary region. It occurs along brook and river banks and mouths of tributaries.

The most common species are: *Euterpe oleracea*, *Mauritia flexuosa*, *Raphia taedigera*, *Manicaria saccifera*, *Iriartea exorrhiza*, *Astrocaryum murumuru*, *Bombax aquaticum*, *Quararibea guianensis*, *Matisia paraensis* Huber, *Crudia tomentosa* (Aubl.) Macbr., *Macrolobium acaciaefolium* Bth., *M. bifolium* (Aubl.) Pers., *Campsiandra laurifolia* Bth., *Swartzia acuminata* Willd., *Ormosia coutinhoi* Ducke, *Taralea oppositifolia*, *Dalgerbia menetaria* L. f., *Machaerium ferox* (Mart.) Ducke, *M. lunatum* (L.) Ducke, *Pterocarpus amazonicus* Huber, *Mucuna altissima* (Jacq.) DC., *Ischnosiphon aruma* (Aubl.) Kcke., *Ravenala guianensis* (Rich.) Bth., *Montrichardia arborescens* Schott, *Gnetum nodiflorum* Brong., *Cyperus giganteus* Vahl, *Hernandia guianensis* Aubl., *Licania macrophylla*, *L. heteromorpha* Bth., *Hevea brasiliensis*, *Hura crepitans*, *Buettneria divaricata* Bth., *Symphonia globulifera* L., *Cydista aequinoctialis* (L.) Miers.

In some areas of the estuary almost pure formations of *Mauritia flexuosa* known as "buritizais" were found.

Common floating plants are *Nymphaea rudgeana* Meyer, *Salvinia* sp., *Pistia stratiotes* L., *Eichornia azurea* (Sw.) Kunth, *E. crassipes* (Mart.) Solms, *Reussia rotundifolia* (L. f.) Castell.

For further details consult the detailed paper of Huber (1943).

Estuary campos

The island of Marajó, with an area of more than 40,000 sq. km., has its south-south-west half covered with forest while the rest is natural open fields (*campos*). Other smaller nearby islands in the mouth of the Amazon (Caviana and Mexiana, have *campos* vegetation. The *campos* of Marajó are quite different from the *campos de várzea* cited for the lower Amazon region. The terrain is drier and the grasses not so robust. The grasses rarely exceed half a metre in height, the most important species being of the genera *Panicum*, *Paspalum*, *Axonopus*, *Andropogon*, *Aristida*, *Leptocoryphium*, *Trachypogon*, etc. On *terra firme* (not flooded) typical species of the *campos cerrados* (savannahs) of Central Brazil appear, such as *Tabebuia caraiba*, *Curatella americana*, *Hancornia speciosa*, *Salvertia convallariaeodora* St. Hil., etc. A common species is a native cashew, *Anacardium microcarpum* Ducke.

According to Gourou (1950) and others, not all the terrain of the islands of Marajó, Caviana and Mexiana are of fluvial origin; part is older soils belonging to the *Barreiras* series. Therefore, the *campos* of Marajó are similar to analogous formations on the Pará and Maranhão coasts, such as the *campos* of Bragança and of Perizes.

In the north of Marajó there occur many lakes, ponds and marshes, Lago Arari being the largest. Here grows a rich aquatic flora of attached and floating plants, including *Pontederiaceae*, *Nymphaeaceae*, *Azola*; *Salvinia*, *Utricularia*, *Pistia*, etc. In this region, depressions with water are called *mondongos* while the higher places that do not become flooded are known as *tesos*.

In some areas in the estuary region, such as in the Baía de Guajará, depressions of irregular form occur, a few hectares in area, distributed along the shore of the bay. These are filled with marshes bathed twice a day by the tides. Here grow an abundance of sedges, including cutting species of *Scleria*, some legumes, *Marantaceae*, *Typha*, etc. These depressions are called *pirizais*, while similar depressions in the Oiapoque estuary are called *cariazais*.

The *campos* of the Amazon estuary are very important economically because they constitute the principal cattle-raising region of Amazonia. Owing to the proximity of Belém, the cattle-raisers have a higher cultural level; included among them are many doctors, lawyers and other professionals living in the city. They are interested in breeding and selection and hold annual cattle fairs.

Mangrove swamps

This is not a typical vegetation type for Amazonia. Its species are well known in other regions: *Rhizophora*

mangle L. ("mangue", "mangue verdadeiro"), *Avicennia nitida* Jacq. ("ciriuba"), *Laguncularia racemosa* Gaertn, and *Conocarpus erectus*. Subsidiary species are *Pterocarpus draco*, *Hibiscus tiliaceus* St. Hil., *Anona palustris* L., and *Pithecelobium cochleatum* Mart. In areas of sticky clay (*tijuco*) *Spartina brasiliensis* Raddi ("paratura") occurs with its sharp-pointed leaves that can puncture men's feet.

Rhisophora grows quite far up the estuary, into fresh water, growing all around the island of Marajó. According to Huber, there are two varieties, the typical and the *racemosa*. *Avicennia* penetrates even further up river.

In very sandy soils and on dunes, *Chrysobalanus icaco* ("agiru") is common.

ESTUARY OF THE OIAPOQUE

Introduction

The Oiapoque acts as the frontier between Brazil and French Guiana (included here are also a few shorter rivers that empty directly into the Atlantic). The Oiapoque estuary is only about 100 km. long. On the Guiana side, uplands approach the river, while on the Brazilian side, near the mouth the alluvial plains become quite wide, the *várzeas* of the Oiapoque, Uaçá, Caripi, Urucauá and Cassiporé rivers uniting. This forms a large area of recent sediments, the material coming from the Amazon and being pushed northwards by an ocean current, as previously explained. At its mouth, where the Oiapoque unites with the Uaçá, the exit is very wide and shallow, and to enter or leave by boat it is necessary to pay much attention to the tides. At low tide wide muddy areas become visible, not only along the banks but in the middle of the mouth also.

The *pororoca* originates in this wide part of the mouth and ascends the Uaça up to the place called Encruso at the mouth of the Caripi. In this whole stretch the water is extremely muddy, and cannot be used for drinking even by the Indians, who are not very demanding.

The Oiapoque estuary, properly speaking, does not exceed 100 km., terminating at the Cachoeira Grande Roche, which is as far as the tidal influence reaches. Upstream from here the bed of the river is pure granite, and the appearance of the river changes considerably with the time of year; in the dry season there is only a comparative trickle through its rocky bed.

The Cachoeira Grande Roche is the point of a radical change in the Rio Oiapoque. The tides terminate there, the landscape changes, and the marginal vegetation and even the fauna change. Many fish species, such as *arraia* and *tucunaré* are not found above this point; from here upstream occur fish species proper to rapids, that feed chiefly on the carpet of *Podostemonaceae* growing on the granite rocks. Even in the estuary, at low tide, some granite blocks may be seen.

The uplands beyond the alluvial plain of the river have a rolling topography. According to Lima *et al.* (1960), the soils in general are reddish-yellow latosoils of the common type in Amazonia, with lateritic concretions (*piçarra*) common in the hills.

The flood-plain vegetation of the Oiapoque region can be divided into *várzea* forest of the Oiapoque proper, *várzea* forest of the lower Uaçá and *campos* of the upper Uaçá.

River Oiapoque

At the mouth there are extensive mangrove swamps, principally of *Rhizophora mangle*, with a few formations of *Avicennia nitida*. From the mouth to Cachoeira Grande Roche the alluvial plain is quite narrow. The chief plants represented, besides mangrove, are a few palms (*Euterpe oleracea* and *Mauritia flexuosa*), dense riverside formations of *Montrichardia arborescens*, *Virola surinamensis*, *Pithecelobium corymbosum*, *P. huberi* and *Pentaclethra macroloba*.

Eperua rubiginosa and *E. falcata* are both common on the riverbank (the former being more frequent), from the mouth to the mouth of the Ingarari, disappearing upstream. Their wood is much used for fences, floors, firewood, construction of docks, etc. Both species are called "apá". Because of their frequency, their long pendulous inflorescences and beautiful violet-rose flowers, these species characterize the riverside landscape.

Bombax aquaticum is a very common species; above Cachoeira Grande Roche it starts to diminish, gradually yielding its place to *B. munguba* and disappearing completely in the middle Oiapoque.

Also common are *Sloanea grandiflora*, *Alchornia* sp., *Quararibea guianensis*, *Combretum cacoucia*, *Tabernaemontana* sp., *Cydista aequinoctialis*, *Callychlamys latifolia*, *Adenocalymma bilabiatum*, etc., and many lianas, especially *Bignoniaceae*.

Lower Uaçá

The lower course of this river has *várzea* forests that are wider than those in the Oiapoque, and which contain a few additional species, but the total number of species is not large. Above the mouth of the Caripi (up to which the *pororoca* reaches) the *várzea* forests start to diminish gradually in height, width and density. Certain species, such as *Triplaris* sp., *Cordia* sp., *Mauritia flexuosa*, *Euterpe oleracea*, *Guadua latifolia* (right at the river bank), *Pentaclethra macroloba*, *Virola surinamensis* and *Carapa guianensis*, which were rarer downstream now become dominant.

Further upriver the forest becomes even more diminished and the grassy *campos de várzea* can be seen behind them. In the forest the leguminous tree, *Macrolobium acaciaefolium*, becomes dominant. It presents a peculiar appearance with its trunk and boughs com-

PLATE V.
Várzea forest in Belém, where flooding is caused by the tides.

PLATE VI.
Várzea forest in Belém, at the Instituto Agronômico do Norte, showing a drainage canal and some clearings. The vegetation near the river (the Guamá) is primary forest.

PLATE VII.
Campos de várzea in the Uaça river region.

pletely covered with the bromeliad, *Tillandsia bulbosa*, along with certain other epiphytic *Araceae* and orchids with inconspicuous flowers. Here, behind the *Macrobium*, can be seen hummocks of *Mauritia flexuosa* scattered over the *campo de várzea*. Further upstream, the *várzea* forest and the hummocks of *Mauritia* practically disappear, giving way to the pure *canarana* of the *campos de várzea*.

In the whole stretch of the river where gallery *várzea* forest occurs, of whatever composition, the forest can be interrupted by areas of marsh that, physiognomically, suggest the idea of a transition to the *campos de várzea*, but they are of a completely different species composition from the latter. These patches of marsh contain robust sedges such as *Cyperius giganteus*, *Eleocharis* sp., etc., along with *Thalia geniculata*, *Montrichardia arborescens*, *Eichornia azurea*, *E. pauciflora*, *E. crassipes*, etc. A marsh of this type is called a *cariazal*, and is similar to the above-described *pirizal* marshes of the Baía de Guajará.

Upper Uaçá

In this region occur the vast expanses of *campos de várzea*, which begin with the disappearance of the *várzea* forests as related above (Plate VII). These *campos* occupy the larger part of the flood-plain vegetation of the Uaçá region in general, reaching east to the banks of the Cassiporé. The vegetation is almost purely one of robust grasses, and is very similar in appearance and structure to the *campos de várzea* of the lower Amazon treated above. This affinity of two Amazonian vegetations in regions so distant from each other was not previously known in the literature and was discovered by myself and personnel of the New York Botanical Garden in a joint expedition to the Oiapoque region in 1960.

The most common species in the Uaçá *campos* are *Oryza perennis*, *O. latifolia*, *O. grandiglumis*, *Echinochloa polystachya*, *Luziola spruceana*, *Panicum elephantipes*, *Hymenachne amplexicaulis*, *H. donacifolia*, *Leersia hexandra*, etc., thus the same as those in the ower Amazon. In the lower places non-grasses, such as *Montrichardia arborescens*, *Thalia geniculata* and *Polygonum acuminatum*, can be found.

This whole *campos de várzea* region is extremely rich in fish, *tracajás* (small turtles) and aquatic birds. On the other hand, the same conditions are also optimum for mosquitoes, whose bites are not only troublesome but also carry malaria.

Our observations refer especially to the Rio Urucauá, one of the tributaries of the Uaçá. Here the *campos de várzea* have a width of 500-1,000 metres on either side of the river, or are so extensive in places that one cannot see where they end, particularly eastward.

The river water of the lower Uaça is, as stated, extremely muddy and more or less brackish at certain times of the year. Because of the *pororocas* the quantity of sediment largely exceeds what may be expected. Above the point reached by the *pororocas*, the water becomes gradually clearer until transparent, although still a bit dark. In certain places, we observed green water undoubtedly caused by algae. The biological condition of these waters should be a very interesting subject because of the tremendous proliferation of fish and turtles and the consequent abundance of aquatic birds such as cranes, ducks, *mergulhões*, *guarás*, etc.

The *campos de várzea* end at a sudden rise in the land where the *terra firme* begins. In the background one can see elevations that exceed 300 metres, such as the mountains of Carupina (330 metres), Tipoca and Cajari. In these higher elevations gold occurs in the soil; it is extracted by extremely primitive methods, such as those used on Tipoca.

When the Instituto Agronômico do Norte heard about the *campos de várzea* of the Oiapoque region, it began a study on the possibility of their being used to raise water buffaloes, and is collaborating with the Army in its plan of development of the frontiers (Lima *et al.*, 1960; Lima and Santos, 1961). A pilot ranch has been set up to raise buffaloes.

ACKNOWLEDGEMENT

I wish to acknowledge the invaluable assistance of Dr. George Eiten in the preparation of the English text of this paper.

Résumé

Les estuaires de l'Amazone et de l'Oiapoque et leurs flores (João Murça Pires)

Cet article traite de la région de l'Amazone en général et plus particulièrement des estuaires de l'Amazone et de l'Oiapoque, ainsi que de leurs flores.

Le cours supérieur de l'Amazone est constitué par la partie du fleuve allant de sa source jusqu'au confluent du Rio Negro. Sa plaine d'inondation (*várzea*), qui s'étend sur 15 000 km^2, est couverte de futaies inondées tous les ans par la crue du fleuve provoquée par les pluies.

Le cours inférieur de l'Amazone va du confluent du Rio Negro jusqu'au confluent du Xingu. Sa plaine

d'inondation, qui couvre 15 000 km², est couverte de forêts dans sa partie supérieure. Sur la moitié inférieure, une forêt clairsemée borde le fleuve avec, derrière, les *campos de várzea*, plaines d'inondation larges de plusieurs kilomètres et couvertes de hautes herbes. L'inondation est provoquée par les pluies annuelles.

L'estuaire de l'Amazone comprend à peu près 25 000 km² de plaines d'inondation. Dans cet estuaire, les inondations sont provoquées par les marées et non par les précipitations annuelles. La plaine basse est donc inondée deux fois par jour pendant presque toute l'année, tandis que la plaine haute n'est inondée deux fois par jour que pendant les marées de vives eaux.

L'article contient des renseignements sur l'importance numérique des peuplements, les essences et le volume du bois sur pied dans les plaines inondées des régions de Breves et de Belém. On y trouve également des données sur la forêt basse qui s'étend sur des terres nouvellement formées, ainsi que sur les herbages de Marajo et d'autres îles voisines.

Des renseignements détaillés sont donnés sur la végétation des plaines d'inondation de l'Oiapoque et de l'Uaça, aux confins de la Guyane française. L'Oiapoque et le cours inférieur de l'Uaça sont bordés de forêts. Le rideau forestier qui borde l'Uaça s'amincit progressivement au fur et à mesure que l'on remonte le fleuve. Derrière ce rideau s'étend jusqu'aux terres hautes une plaine d'inondation couverte de hautes herbes. Finalement, le rideau forestier qui borde le fleuve disparaît et il ne reste plus que la plaine herbeuse. La région est extrêmement riche en poissons et en oiseaux aquatiques et convient particulièrement bien pour l'élevage du buffle d'eau.

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Some factors involved in mangrove establishment

V. J. Chapman

The occurrence of mangroves in salt water habitats has for long excited the interest of botanists. It is evident that at all stages of growth the plants must be able to tolerate flooding of the root system by salt water. In the case of pioneer species this will be a daily occurrence, whilst in the case of those at higher levels it will be less frequent. In the former the salt concentration will barely rise above that of the flooding water, but in the latter during neap tides evaporation from the soil surface may result in a significant increase of salinity (Chapman, 1944). Salinity tolerance may not, however, be the only factor that determines whether a species can grow in mangrove swamp or salt marsh habitats. Whilst the occurrence of any predominant species in a given environment is commonly explained in terms of the external physical or biotic milieu, the physical environment must impinge upon the metabolic processes that result in growth and reproduction. Of these the two most important are respiration and photosynthesis.

So far as mangroves are concerned very little work has been carried out on either respiration or photosynthesis. In the case of the latter process one would anticipate that in the adult plants the rate is not dissimilar from that of other forest trees in like climate. Golley, Odum and Wilson (1962) studied the productivity of a red mangrove forest in Puerto Rico and came to the conclusion that it is more productive than most marine and terrestrial communities. On the other hand it is not so efficient as montane rain forests or a coral reef in the conversion of sunlight to organic matter under similar light régimes.

So far as the writer is aware no attempt has been made to determine the effect of high salt concentration upon the rate of photosynthesis. It could well be that decreasing the salt in the foliage brings about an increase of photosynthesis. An answer to this question could only be obtained by growing plants under controlled salinity conditions. The mere fact that mangroves are not commonly found under freshwater conditions suggests that, even if the rate of photosynthesis is more rapid under low saline or in freshwater conditions, this is not of itself sufficient to enable them to grow under such conditions. If the adult plant cannot grow successfully under freshwater conditions we have still to inquire whether photosynthesis is affected at any other stage under maritime conditions. At this point we neglect the adult plant and consider the young seedling. In many mangroves, especially pioneer species, the plants are viviparous and the young seedling drops off the parent tree and either sticks in the mud below or is carried away by the tide. In the former case contact with the ground provides a stimulus that initiates adventitious root growth, though the initials may be already present within the hypocotyl. If the seedling is carried away by the tide quite a time may elapse before it becomes stranded. During this period root development does not occur, or if it does is extremely slow, nor are there other visible signs of growth. What is it in the ground that stimulates root growth and consequent anchorage which is lacking in the sea? Possibly some hormonal mechanism is set in motion and solid ground is more effective in initiating this than a liquid medium. Evidence in support of this may be given by root development only on the soil side of *Rhizophora* seedlings lying on the ground (La Rue and Muzik, 1954). From the point of view of effective establishment a seedling such as that of *Rhizophora* or *Bruguiera* has more chance if no roots have developed whilst floating than if there were a mass of them. When a seedling of either genus first becomes stranded the development of the adventitious roots is such that the young plant automatically becomes pulled into an erect position. This would not be possible if there were already a mass of roots.

Apart from the mechanical effect of attachment and erection no work appears to have been done on floating seedlings to see whether any photosynthesis takes place under such conditions of immersion, nor has any work been done on young attached seedlings to determine

the effect of regular submersion and exposure upon photosynthesis (and hence rate of growth). The young mangrove seedling has not only to tolerate periods of submersion, when it is probable that photosynthesis is inhibited because of inhibition of CO_2 supply, but in most areas a distinct deposit of mud can be laid down upon the leaves. Indeed it is very easy to determine the maximum height of tidal rise in a mangrove swamp by looking at young seedlings and observing the level at which leaves no longer have a mud covering. Such a mud covering must reduce the quantity of light penetrating the leaf and may also reduce the rate of gaseous diffusion. Here again we are in a realm where there is no information. One can indeed suspect that there is a level on the mud flat where the period of submersion is too long for the young seedling to photosynthesize sufficiently to meet the catabolic needs so that growth is impossible. Studies of seedling response in respect of photosynthesis and respiration whilst submerged and exposed should enable the lowest level of possible establishment for the various species to be determined.

The high concentration of salt in the soil undoubtedly means a slower rate of water uptake, slower upward water movement in the trunk and a slower transpiration loss as compared with many other tropical trees. The over-all net result would contribute towards a slow growth rate as compared with trees growing under adjacent mesophytic conditions.

The mangrove habitat is normally that of a mud flat though mangroves will also grow on sand flats, coral reefs and in areas where their roots result in the development of a peat soil (Chapman, 1944). In the mud and sand flats waterlogging of the roots occurs for much of the time, particularly at levels where pioneering is proceeding. Additionally in the mud there is evidence of little gaseous exchange and provision for this phenomenon is provided for in many species by special roots (pneumatophores), though the efficacy of these may be limited to short lengths of underground root (Troll and Dragendorff, 1931; Chapman, 1944). Again, however, very little work appears to have been carried out upon the effect of the environment on respiration, and more particularly upon the respiration of the young seedling after it has dropped from the tree and is either floating in the sea or starting to grow in mud beneath the parent tree.

Some years ago I noted that seedlings of *Avicennia marina* (the sole mangrove species that is found in the northern part of New Zealand) produced a gas bubbling phenomenon after 24 hours immersion in water and that this could continue for some days. Separation of seedlings from the fruit walls enhanced the process, especially in the case of the fruit walls where autolysis is probably initiated. In the case of the emergent seedlings autolysis is unlikely nor could they at that stage be harbouring bacteria. It seemed likely therefore that anaerobiosis was actually taking place, and since this is not a normal occurrence in green plants it appeared that the capacity for anaerobiosis, if confirmed, might be of ecological significance. The oxygen tension in sea-water is low (5 ml. per litre at 25° C.) and it was conceivable that a capacity to respire anaerobically might enable the seedlings to survive whilst floating in sea-water, though not providing sufficient energy to enable active growth to commence. Even so, it has been calculated (James, 1953) that for apples, at least, the ratio of energy turnover aerobically to that anaerobically is 710 to 317 and that the anaerobic turnover is much in excess of any requirement shown to exist in plants. It could in fact well be that growth of the seedlings whilst floating in sea-water is related to lack of sufficient oxygen for oxidases or other processes essential to growth.

Whilst experiments with floating seedlings of *Rhizophora mangle* produced no evidence of gas bubbling like that of *Avicennia*, it nevertheless seemed worthwhile to study the part played, if any, by anaerobiosis in mangrove seedlings as a whole. If the phenomenon proved to be substantial one could then consider its relation to the type of habitat in which mangroves occur and also its significance, if any, in respect of seedling survival and establishment. The capacity of a young seedling to respire anaerobically would not necessarily represent an adaptation to the environment, though it might be interpreted as meaning that because the species possess this capacity (and may have always possessed it) they have been enabled to invade this particular environment and survive instead of being exterminated.

The initial work was carried out with *Avicennia marina* seedlings, a species of wide distribution, but subsequently seedlings of *Rhizophora apiculata* and *Bruguiera gymnorhiza* were employed and then an opportunity to visit the West Indies, and later Florida, enabled work to be carried out on seedlings of *Rhizophora mangle* and *Avicennia nitida*. Small and large seedlings were used in both species of *Avicennia*, the small ones intact but the larger had to be sliced in order to place them in Warburg flasks. Sliced mature seedlings of both species of *Rhizophora* were employed, as also of *Bruguiera*, but in the case of *R. mangle* three successively smaller seedling sizes were used, the two smallest not having emerged from the fruit wall.

Early experiments soon indicated that the fruit wall exercises a marked inhibition on the respiration rate. In general intact seedlings have a respiration rate that is about five-eighths that of seedlings with wall removed, irrespective of whether they are submerged or in a humid atmosphere (Fig. 1). Further experiments also indicated that when the fruit wall broke away and liberated a seedling there was an immediate rise in the respiration rate. This was very evident when experiments were carried out over a number of days. Bharucha and Shirke (1947) have also found a similar increase in the respiration rate of seedlings of *A. officinalis* when the fruit wall was removed.

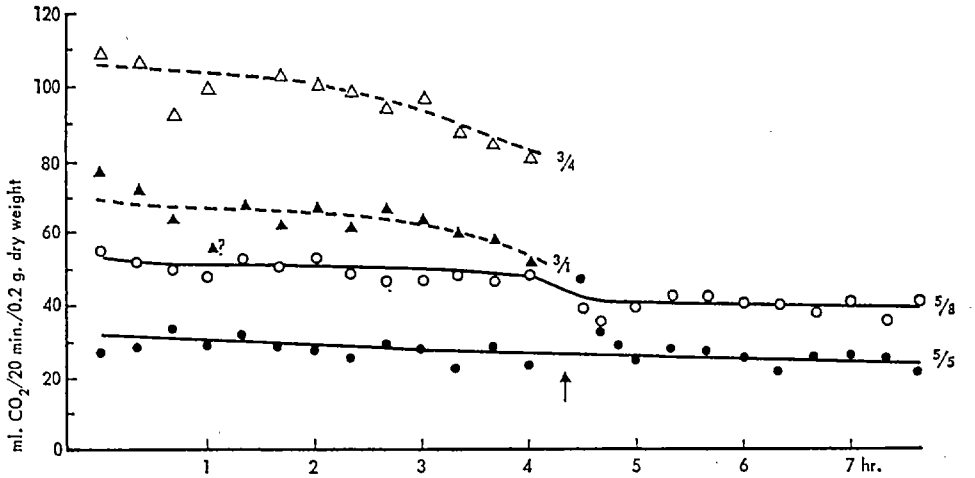

FIG. 1. *Avicennia marina.* Respiration rate of small, intact seedlings (experiments 3/1 and 5/5) and seedlings with testa removed (experiments 3/4 and 5/8). In experiment 3 the seedlings in 3 ml. distilled water, in experiment 5 in humid atmosphere. Average respiratory quotient: experiment 5/5 = 0.98, experiment 5/8 = 0.96.

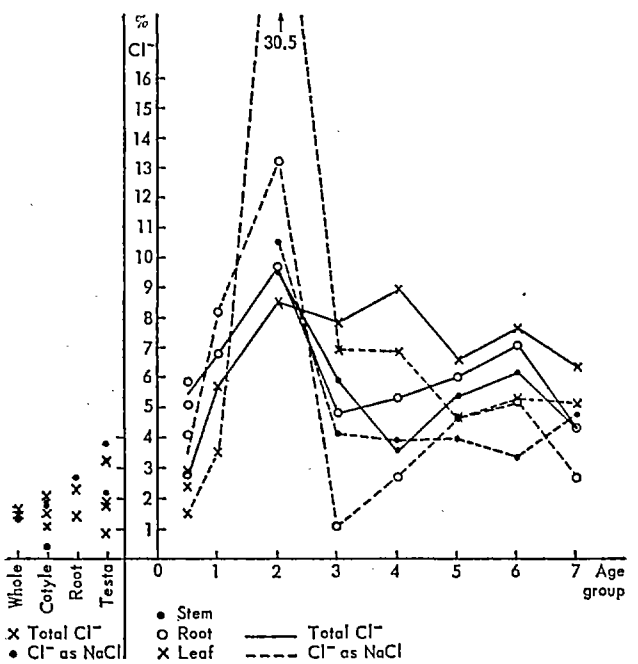

FIG. 2. Total Cl^- and Cl^- equivalent of Na^+ in age series of *Avicennia* seedlings.

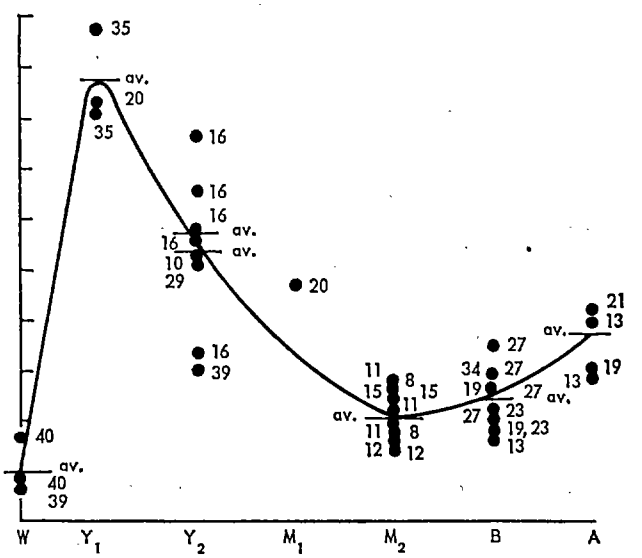

FIG. 3. Summary of respiration rates of different aged *R. mangle* seedlings in 3 ml. sea-water (Y = young, M = medium, B = base, A = apex of mature seedling).

In the case of young seedlings of *Rhizophora mangle* the respiration rate in distilled water was two to three times higher than that in either natural or artificial sea-water, though in the case of a mature seedling this difference had disappeared. During seedling growth on the parent tree there is probably a gradual entry of some salt even though there is a form of exclusion mechanism (Chapman, 1944), though this is apparently less effective in *Rhizophora* than in *Avicennia.* When the mature *Rhizophora* seedling drops, therefore, there will not be any great effect upon respiration rate. In the case of *Avicennia* the seedlings are far more sensitive and the rate in distilled water is double that in sea-water. During growth on the tree there is an effective mechanism for inhibiting the entry of salt into the young seedling and when it falls there

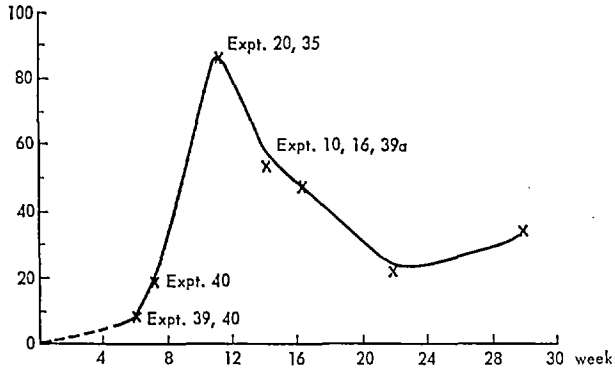

FIG. 4. Mean respiration rate of *R. mangle* seedlings at different stages of growth. The curve in the very early stages is hypothetical (broken line) and does not start at zero.

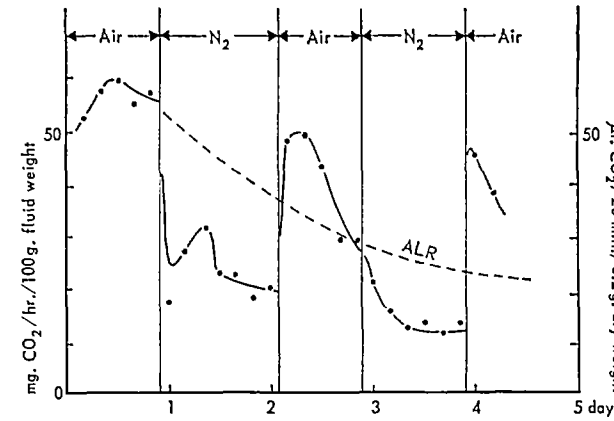

FIG. 5. *A. marina.* CO_2 output of whole seedlings in CO_2-free nitrogen and air at 25° C. in the dark. The periods in each gas and the times of transfer are indicated by the vertical lines. Air line respiration (interrupted line ALR) obtained by extrapolation.

is an immediate uptake of salt (Fig. 2). This phenomenon is therefore likely to be associated with a sudden reduction in respiration rate, and the ability of *Avicennia* to colonize must rest in part with the capacity of the seedling to respond to these sudden changes. Walter and Steiner (1936) have demonstrated a similar phenomenon for old world mangrove species.

A study of the ontogenetic drift in respiration rate of *Rhizophora mangle* shows that the very youngest seedlings have the lowest respiration rate and that this rises sharply, after which it falls with increasing maturation of the seedlings. The phenomenon is the same irrespective of whether the seedlings are immersed at each stage or whether they are in a humid atmosphere (Fig. 3). The mean rate for the plumular portion of a mature seedling (A) is also higher than that of the hypocotyl base (B), though at earlier stages of development the reverse is the case. Based upon a consideration of age of seedlings the respiratory drift in *R. mangle* can be summarized as in Figure 4, the respiration rate probably being very low during the first six weeks after fertilization though it is probably never zero. A comparison of the respiration rate of *Avicennia* seedlings with that of their fruit walls showed that the latter had a much higher respiration rate than the former, and this greater metabolic potentiality could well be associated with the greater degree of gas production shown by fruit walls when floated in water.

A comparison of the respiration rate of different species showed that the hypocotyl bases of *Rhizophora mangle* and *R. apiculata* had about the same respiration rate whereas the hypocotyl base of *Bruguiera gymnorhiza* has a rate one-half to two-thirds that of the *Rhizophora* species.

The most important aspect, however, is the behaviour of these seedlings under anaerobic conditions and in atmospheres with reduced oxygen tensions. Work on this aspect has been carried out by Dr. J. M. A. Brown of my department and I am grateful to him for permission to use material that at present is being prepared for publication.

It has been noted that seedlings of *Avicennia marina* washed up on shores around Auckland have a characteristic "fruity" odour, compararable to that produced when seedlings are floated in water for 24 hours or more, or when they are placed in O_2-free atmospheres for 24 hours or more. The presence of ethanol in these seedlings has been confirmed qualitatively, so that whilst immersed in sea-water the plants may well undergo low oxygen zymasis. The effect of transfer of *A. marina* seedlings from air to nitrogen and back again over a series of days is shown in Figure 5, the rise on the first transfer being due to the shedding of fruit walls. Similar rises were evident in a Pettenkofer experiment where a number of seeds were involved.

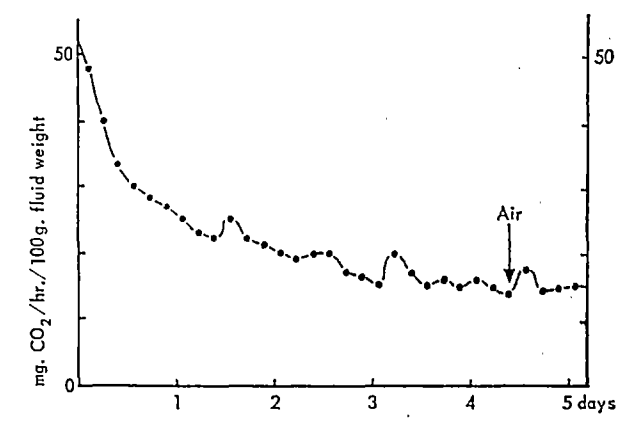

FIG. 6. *A. marina.* CO_2 output of whole seedlings in CO_2-free nitrogen at 25° C. in the dark. The plants were transferred to air after 4½ days.

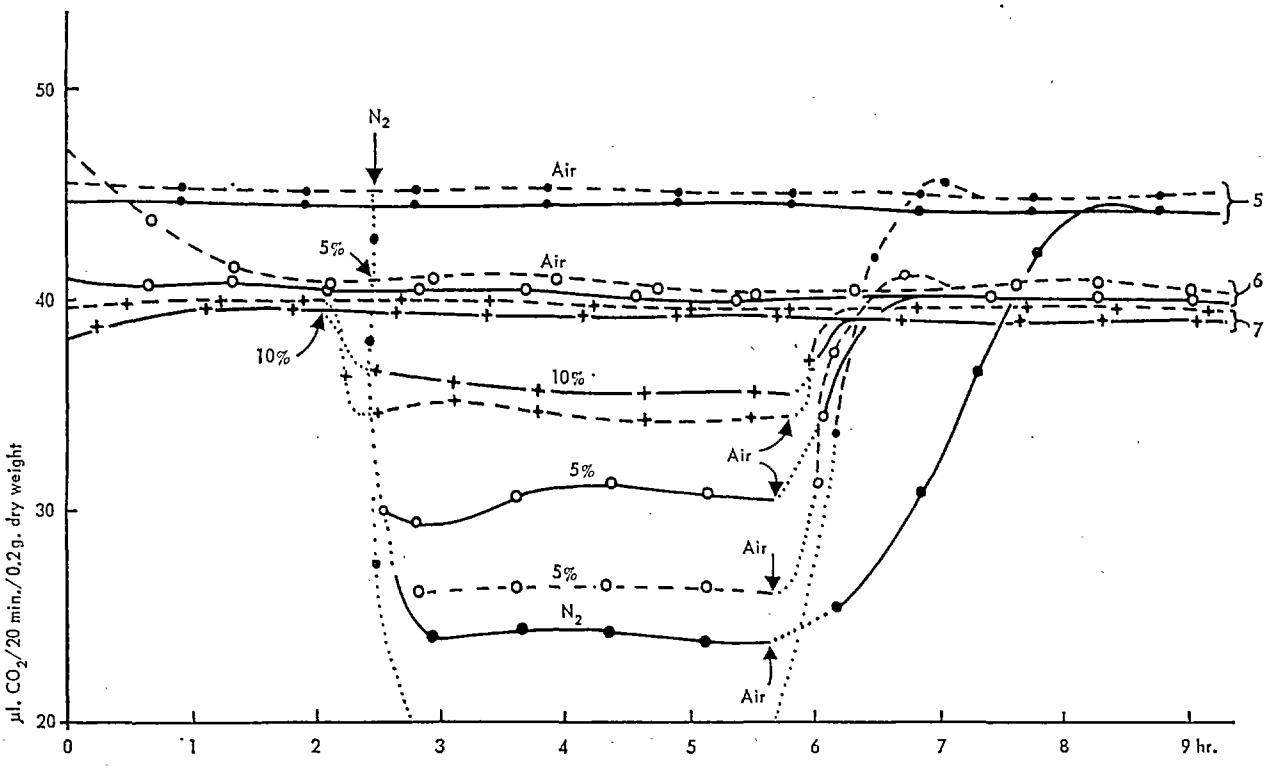

FIG. 7. *A. marina.* Oxygen uptake and CO_2 output of tissue slices suspended in 3 ml. sterile sea-water at 30° C. in air throughout and in N_2, 5 per cent O_2. and 10 per cent O_2. Each line represents the smoothed curve and individual points are for identification only: •, o and + represent three different experiments. Interrupted lines = O_2 uptake; solid lines = CO_2 output; dotted line = transition period. Times of transfer to each gas and of the return to air are indicated by arrows.

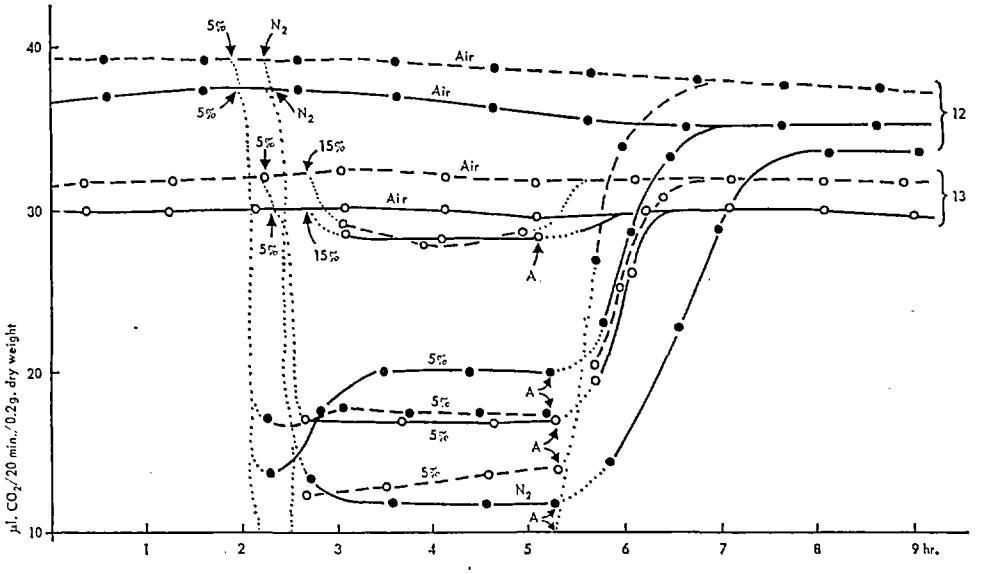

FIG. 8. *R. conjugata.* Oxygen uptake and CO_2 output of hypocotyl slices suspended in 3 ml. sterile sea-water at 30° C. in air throughout and in N_2, 5 per cent O_2 and 15 per cent O_2. Each line represents the smoothed curve and individual points are for identification only: • and o represent distinct experiments. Interrupted lines = O_2 uptake; solid lines = CO_2 output; dotted lines = transition period. The times of transfer to each gas and of the return to air (A) are indicated by the arrows.

and the testas shed at intervals (Fig. 6). It will be noted that on return to air from nitrogen the CO_2 output is distinctly stimulated. This stimulation was observable in all experiments of this nature.

When transferred to nitrogen the rate of respiration in *A. marina* drops to about 55 per cent that in air (air line respiration), whilst with reduced oxygen tensions the drop is less (Fig. 7). In *Bruguiera gymnorhiza*, a similar pattern is evident, the respiration rate in nitrogen being 45-50 per cent that in air (Chapman, 1962; Brown, unpublished). The effect of lowered oxygen tension is very much more marked in *Rhizophora apiculata* where the rate in nitrogen is only about one-quarter to one-third that in air (Fig. 8). It would seem therefore that an anaerobic component of respiration is more significant in the first two species. It would be of considerable interest to determine the rate in other mangrove species and genera and at present arrangements are being made for this to be done. Variation can occur within a genus because data for *R. mangle* indicate that the rate in nitrogen is comparable to that of *Bruguiera* and the effect is there fore not so pronounced as in *R. apiculata*.

An analysis of the relative energy released under wholly anaerobic conditions shows that it would be inadequate for growth unless lactic fermentation accompanies the zymasis. On the other hand one can note that in nature practically no growth occurs so long as the seedling is floating in sea-water, and it is only after a seedling has stranded and is subject to periods of non-immersion that active growth takes place. It may well be, therefore, that anaerobiosis only plays a part during periods of submersion. It must, however, be borne in mind that *Avicennia* seedlings have a considerable aerenchyma (Chapman, 1944), and so long as photosynthesis is taking place there may be an accumulation of oxygen internally. At present, however, we have no data on photosynthetic rate when *Avicennia* seedlings are floating in sea-water. The relative proportion of aerenchyma is less in seedlings of *Bruguiera* and *Rhizophora* and the greater size of the seedling could bring about internal anaerobic conditions when floating in water.

In conclusion it is evident that mangroves possess some features, e.g., vivipary, capacity for high salt tolerance, and possibly also capacity for anaerobiosis, that enable them to grow successfully under conditions that are less than optimum. Such information as is available shows that rooting and early growth is more successful under fresh than under saline conditions (La Rue and Muzik, 1954), but even then it is evident that growth is not at a rate which is competitive with other terrestrial trees, and the young mangroves would rapidly succumb. It may well be that the adults at least are light demanding though the young saplings certainly do not seem to be. In the case of *R. mangle* La Rue and Muzik (op. cit.) report that although hypocotyls may reach as much as 46 cm. in length they will not root or anchor in water deeper than 20 cm. Failure to root in greater depths may either be a mechanical phenomenon associated with water movement, or it may be that insufficient of the plant remains above water to provide aerobic energy to enable the anchoring roots to grow out.

Whilst we are in a much better position today to interpret the niche that mangroves occupy, it is apparent that there is still plenty of scope for further work, especially in analysing the effect of external conditions upon photosynthesis and respiration.

Résumé

Facteurs influant sur l'implantation de la mangrove (V. J. Chapman)

Les espèces de la mangrove peuvent supporter l'inondation de leur système radiculaire par l'eau salée, mais on ne sait presque rien des effets de ce facteur physique et d'autres facteurs mésologiques sur les processus du métabolisme, en particulier la photosynthèse et la respiration. Il se peut que les plantes adultes supportent des milieux salins très divers, mais de nombreuses espèces de la mangrove se caractérisent par des plantules vivipares. On ne connaît pas les effets de l'eau salée sur le taux de photosynthèse ni celui des inondations périodiques sur ce processus. Il se peut qu'à un certain niveau des fonds vaseux la période de submersion soit trop longue pour que la jeune plantule ait un métabolisme suffisant pour répondre aux besoins de son catabolisme. De même, on n'a guère étudié la respiration des jeunes plantules vivipares qui flottent sur la mer ou qui commencent à peine à se développer. On a étudié certaines espèces de la mangrove pour déterminer la mesure dans laquelle la respiration de leurs plantules est anaérobie, et si cette proportion est assez importante pour exercer une influence sur la situation écologique des diverses espèces. Le taux de respiration des plantules d'*Avicennia* est influencé par la teneur en sel et comme les plantules absorbent une grande quantité de sel en tombant dans l'eau de mer, il en résulte peut-être un fléchissement soudain du taux de respiration et, par consé-

quent, une diminution de l'énergie disponible pour la croissance. Il n'en est pas de même de *Rhizophora mangle*. Dans des conditions d'anaérobiose, la respiration ne cesse pas, mais elle tombe à 55 % environ de la respiration à l'air libre chez *Avicennia marina*, à 45-55 % chez *Bruguiera gymnorhiza* et à 25-35 % chez *Rhizophora apiculata*. Ce ralentissement du taux de respiration est assez semblable à celui qui se produit lorsque les plantules flottent dans l'eau de mer, où la tension de l'oxygène est faible. Il faut maintenant faire des recherches afin de déterminer le taux de photosynthèse dans des conditions analogues et si l'aerenchyme est suffisamment oxygéné pour répondre aux besoins anaboliques. On constatera sans doute que le développement est loin d'être optimal en milieu marin, et il apparaîtra peut-être qu'en fin de compte les effets de la teneur en sel sur la respiration contribuent puissamment à réduire la croissance au point où l'espèce considérée ne peut plus rivaliser avec les autres espèces d'eau saumâtre.

Discussion

V. J. Chapman. I have seen the zonation to which Dr. Fosberg refers, and in Malaya a very complicated zonation exists which is evident on air photos and also from ground survey. The natural inclination is to relate this zonation to salinity but I believe other factors are involved as well—for example, degree of waterlogging, degree of soil aeration, response of seedlings to flooding. Far too little work has been done upon the response of mangroves to factors other than salinity, and even the response to salinity itself, to enable one to be in any way dogmatic. There is a wide open field for study before any clear answer can be given to your question.

B. A. Abeywickrama. I have not studied the aspects now presented to us by Professor Chapman, but I think that the form of the root system is one of the important factors which determine the places where mangroves can establish themselves. Most sandy sea-shore plants have deep root systems. For example, *Ipomoea pescaprae* on germination, after the unfolding of the cotyledons, produces a long tap root which runs 2 to 5 feet down to the water table. It is only then that the shoot system develops further.

Mangrove seedlings, as far as I am aware, have only shallow root systems. Young seedlings of *Rhizophora* or *Bruguiera* are often found on the sandy shores of Ceylon. Older stages however, are absent. They probably die down when the sands dry up. They seem to be capable of establishing themselves only in places where the water table is high.

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Vegetation as a geological agent in tropical deltas

F. R. Fosberg

A delta is a mosaic of deposits of loose, fine-grained alluvium, principally silt and sand, mostly saturated with water, and inherently unstable but tending to be stabilized by vegetation. These deposits are separated by and interspersed with channels and bodies of water.

The basic arrangement of these features is simple. A river, towards its mouth, splits into a fan-shaped arrangement of channels called distributaries, through which its waters enter the ocean. These are lined on both sides by strips of land called natural levees, which become lower towards the mouths of the distributaries. Between these distributaries, towards the head of the delta, may be remnants of older deltas in the form of terraces. Farther down, the distributaries are separated by large basins, either of open water or filled in to form swamps and marshes. The swamps and marshes are drained by tortuous channels that originate within them. Around the seaward margin are continuous or broken sand ridges. At the mouths of distributaries the delta may grow by extending fingers, usually double linear deposits of silt, into the sea, or turbulent water and currents may restrict this type of growth. In most actual deltas this simple pattern has been much obscured by irregular growth, shifting of channels and storm damage. This blurring of the pattern has, in many deltas, been greatly emphasized by human agricultural and engineering activity.

In the tropics especially, most rivers are subject to great fluctuations in water level, and consequently their deltas are frequently flooded. The floods tend to shift and rearrange the sediments and to deposit more, especially silt, thus adding to the levees and silting up the basins. Accumulation of silt in the channels increases this propensity to flooding. In some regions, such as South-East Asia, typhoons and hurricanes also cause catastrophic floods.

One of the principal factors tending to counteract this shifting and instability in a delta complex is vegetation, several types of which are very characteristic features of deltas. The best known of these are salt marshes and mangrove swamps. Freshwater swamps and marshes, as well as peat swamps, are very extensive also.

The principal physiographic features of deltas may be classified as follows (in part following the ideas of Esther Aberdeen Holm);

1. Water:
   (a) distributaries;
   (b) delta channels and tidal channels;
   (c) lakes and ponds: interconnecting basins, levee flank depressions, abandoned channels, including ox-bow lakes.
2. Wet lands (filled lakes and ponds).
3. Dry lands:
   (a) delta terraces;
   (b) natural levees;
   (c) sand ridges and flats.

Each of these land forms is influenced in some measure by vegetation, and the relationships will be briefly brought out in the following paragraphs. It must be understood that these remarks are based on very inadequate observation, mostly made incidentally in the course of other work. Studies of the role of vegetation in humid tropical deltas, or even of any aspect of the vegetation of these deltas, are few, except for works on mangrove swamps. Some of what would seem the more obvious phenomena of delta vegetation are not at all adequately understood.

WATER

One of the most pervading and ever-present features of deltas is water. This comes from three sources: the river, rain and the sea. The water level in most parts of a delta fluctuates with the tide. Tidal influence brings about a mixing of salt and fresh water along the seaward margin of the delta, and a salinity gradient is established between the fresh water in the headward parts of the delta and the salt at the outer margins.

This gradient profoundly affects the distribution of plants and vegetation types. The tidal fluctuation also exposes sand banks and mud banks, at times long enough that certain plants may become established. The average periods of inundation and exposure may have a decisive role in determining which plants may grow in certain areas, and consequently the distribution patterns of certain vegetation types.

Distributaries

These, the main branches through which the river empties into the sea, tend to be the larger channels in the delta, and range from relatively straight to meandering with large curves. They are arranged fan-wise, forking and spreading out, and often becoming very wide in their lower reaches. They are normally lined on both sides by strips of land called natural levees, which become heavily vegetated. This vegetation, by stabilizing the levees, constrains the channels of the distributaries and lessens their shifting. On the convex side of a meander the vegetation tends to be cut away by the current, while on the concave side, silt and sand tend to be deposited and a footing is provided for mangrove vegetation. Because of the relatively strong currents rather little floating vegetation accumulates in the active distributaries, and transported sediments even tend to scour the bottoms clean of submerged aquatic plants. However, during low-water periods water hyacinth (*Eichhornia*) may form a solid blanket over the surface of at least the more sluggish distributaries. Where these are used for navigation this growth may at times become a great nuisance. During flood season, such vegetation is usually swept out to sea or into the lakes and ponds. Then, also, the distributaries may frequently shift their courses. This happens for two reasons. The natural levees that contain the channel are built up higher than the intervening basins. As the level of the water in a distributary rises during the season of high water, it may be substantially higher than that in the basins, so that any weak point in the levee, usually a break or thin place in the vegetation, may be cut through. Also, as silt-laden water in the distributary slows down it tends to deposit so much silt that the channel can no longer carry the water, and it overflows.

Delta channels and tidal channels

Channels that originate in the delta itself, draining the lakes, ponds, swamps and marshlands, tend to be closely meandering and intricately branched. This pattern is striking, very uniform, and immediately identifiable from the air or on an aerial photograph. Its origin is not very clear, though it is undoubtedly related to the near lack of any slope and consequent low cutting or scouring power of the tidal currents. The water escaping through these channels is from rain floods, and that which entered at high tides. In frequently flooded or actively tidal areas, the water in these channels tends to be turbid, or sometimes greenish. Where there is little outside influence, and the water is mainly rain or ground water, it is clear; more often it may be black, showing the presence of peat in the swamps. Vegetation tends to spread into these channels, but since they are almost invariably open, except for floating plants, an equilibrium must exist between the effects of the moving water and the vegetation. Floating plants may, at least locally, cover the water of these channels completely, but this is not as common as might be expected.

It is probable that in most deltas all or most of the water channels are influenced by the tides. However, the term delta channel may well be reserved for those where the tidal influence is slight enough that they are filled with clear or black water. True tidal channels, obviously under tidal influence, may anastomose in their lower reaches and form a network, isolating islands of marsh or swamp. Tidal and delta channels ordinarily form only very slight natural levees along their banks, or none at all.

Lakes and ponds

Bodies of still water are frequent features of most humid tropical deltas. They range from extensive basins down to small ponds and pools. Some have outlets, others do not. All have a tendency to fill with sediments and plant remains and to change gradually to marshes or swamps. The salinity in those that are connected with distributaries by tidal channels tends to approach that of the part of the delta in which they are located. The ones that have no outlet, or outlets closed by bars of sand or silt, tend to contain fresh water, often sour black peaty water. Because they are not subject to active tidal influence they may be much less brackish than their position in the delta would suggest. All tend to have both submerged and floating vegetation. The dead remains of this, as well as of the surrounding vegetation, accumulate as peat if the nutrient status of the water is low, as a slimy muck or as a component of silt or clay deposits if it is high. On the basis of origin, these water bodies may be grouped into three categories.

Interconnecting basins. These originate as areas of shallow sea cut off by sediments deposited as the delta builds outward, and natural levees, sand bars, and ridges form. At first they may be practically open to the sea—merely deeper areas in the shallow water over the extensive silt deposits of the extending delta. As the features that enclose them build up, become vegetated and achieve stability, the lakes are better defined and more permanent. Unless one happens to be cut by a shift of a distributary so that it is kept somewhat clear by current action, the remains of floating and submerged vegetation and periodic increments of silt from flood-waters will fill it in a relatively

short time. Mangrove swamps form around its shallow margins, especially if tidal currents can bring in the floating plantlets that characterize so many mangrove species, or fruits or seeds of others. In the Old World deltas, *Nipa fruticans* becomes established over large areas. Mangroves and *Nipa* produce large amounts of coarse organic matter and also act as baffles and slow the flood-waters down during periodic inundations, so that they drop more of their loads of sediments. This hastens the change from a lake to a swamp.

Levee flank depressions. The sediments that make up deltas normally contain a large component of water and much organic matter. Organic matter may be especially abundant in the swampy strips along the outer slopes of natural levees. During periods of low water, both decomposition of organic matter and loss of water from the sediments by evaporation and gravity flow take place at greater than normal rates. Compaction and settling, both from the above processes and from slow but continuous action of gravity, tend to produce long narrow ponds aligned along the outer edges of the natural levees. Ponds of similar origin but of different shapes may form anywhere in the delta where for any reason compaction becomes more rapid than accretion of sediments. Such ponds are likely to be choked with floating, submerged and rooted aquatic vegetation. In tropical deltas they are more likely to present the appearance of swamps than of open water, and are likely to fill rapidly with vegetable debris and silt and to be very temporary features.

Abandoned channels or ox-bow lakes. As channels, especially distributaries, fill up with silt, they tend, especially when floods occur, to cut through their enclosing natural levees and assume new courses. This commonly takes place on the seaward side of a seaward loop of a meander, and the new channel, being straighter at first, takes most of the water. The old is soon cut off by newly-formed natural levees and is left as a lake, often a C-shaped lake, called an ox-bow, of still water. Such lakes are a very characteristic feature of deltas (also of flood-plains) and where they remain undisturbed, showing varying stages of being filled by vegetation and silt, they may reveal much of the history of the delta to a practised eye. More often than not, even while an ox-bow is still too deep for rooted woody vegetation to take hold, the surface is covered by a thick blanket of floating vegetation and of rooted plants with floating leaves, such as water-lilies. The debris from this vegetation, plus silt from floods, eventually fills these lakes, though as they tend to be deeper they may persist longer than other types of lakes and ponds.

WET LANDS

As lakes, ponds, and channels fill with silt and organic debris, they gradually change from areas of permanent standing water to land that, although still wet, is firm enough to support emergent vegetation. The water table usually fluctuates so that the surface is inundated for a part of the year, or, tidally, for periods of a few hours. The soil tends to become compact during periods of emergence and to retain its compactness during submergence. Accretion of silt and organic matter continues, the silt being added as long as the land continues to be flooded. In the tropics the vegetation of such land tends to be woody—trees or shrubs—and the ecosystem is called a swamp. Marshes and wet savannahs, with herbaceous vegetation, are, however, not completely lacking. Areas of wet sand, with the water table near the surface of the sand, are frequently covered by grasses, sedges and other herbs, with or without scattered shrubs and trees, and are termed wet savannahs. Where trees become dominant in such wet sandy areas, peat accumulates, and a peat swamp results. Wet savannahs and peat swamps usually occur well away from the strongly salty end of the salinity gradient, toward the head of the delta. They are also confined to areas where the water supply is principally rain and ground-water seepage rather than floods. Perhaps the low mineral content of such waters and the low-nutrient status of the sand are responsible for the peat accumulation in these situations, because the resulting plant debris may not provide a very nutritive medium for decay-producing organisms. It may also be suggested that the acidity of this water inhibits the growth of the bacteria and fungi that normally bring about rapid decay of dead plant parts.

In areas subject to flooding and active tidal inundation, with silt accretion, other kinds of swamp and marsh vegetation are found. Swamp is the rule. Toward the head of the delta, various trees adapted to inundation by fresh water dominate these swamps. Limited areas of marsh, often dominated by reeds and other tall grasses, occur. I will suggest no general explanation of these, except that perhaps the grasses become established and abundant early and that it may be difficult for trees to colonize a dense stand of reeds. Toward the sea, the swamps are more and more dominated by mangrove plants of various species. Where the salinity is significantly high, mangrove vegetation in the Old World, including *Nipa*, dominates large areas. In the transition zone between freshwater and mangrove swamps, mangroves and *Nipa* line the larger tidal channels, and freshwater-swamp trees dominate away from the channels in the interior of swampy islands. Salt-water floods may, in some deltas, at least temporarily shift the salinity gradient upstream, with an effect of extending mangroves inland. Differing salt tolerances of the various species tend to bring about a rather conspicuous zonation of different swamp types as the sea is approached.

Swamp trees, especially the mangroves, tend to form a very substantial root mat, and to have many ingenious types of pneumatophores or aerating organs.

These may take the form of stilt roots, knees, thin sinuous buttresses, bulbous swellings, and what appear to be inverted roots, growing vertically upward. The resulting vegetation makes a very effective silt-catcher and resists disturbance by floods. Silt accumulation may be rather rapid in swamps. In Old World deltas, the *Nipa* palms often have buried vertical or ascending stems as much as 1 or 2 metres long. It can be assumed that the plants grew upward as the silt accumulated around them. While their life span is not known, this gives us some idea of the rate of silt deposition.

The role of vegetation in the wet-land areas just described seems twofold. It tends to add organic matter to the sediments in the form of fallen leaves and twigs, roots, and fallen branches and trunks. It also slows down the rate of flow of flood-water and causes more abundant deposition of silt and other grades of sediment.

DRY LANDS

Dry land is a relative term, especially when applied to deltas, as any land in a delta has a high water table and most are subject to relatively frequent flooding. However, land that is above water long enough that it is usually ordinary moist or dry earth, rather than mud, is regarded as dry for our purposes. Such land, in tropical deltas, takes three forms, and all are vegetated. They differ in location on the delta, nature of the sediments, degree of soil development and in the nature of their vegetative cover. The vegetation plays three important roles in these situations. The primary role is in stabilizing the sediments. Contributing organic materials directly to the sediments and influencing soil development are the other two.

Delta terraces

On many deltas, there are erosion remnants of former delta land surfaces that formed at higher sea levels. They are flat or very gently sloping platforms, found near the head or the landward margins of the present-day deltas. The surface may show some slight relief that is due to erosion, or even persists from irregularity in the original delta surface. They are normally drier than the rest of the delta. The soil is older and more weathered, often severely leached if the delta is in a rainy region. In very humid regions the vegetation may be the normal lowland rain forest of the region, or more likely secondary forest resulting from disturbance or clearing of the land. Shifting agriculture, or even more permanent agriculture may be practised, but the soil is likely to be rather more sterile than ordinary delta soils, depending on the age and degree of leaching. In dryer or more seasonal regions the vegetation may be savannah, probably burned over annually. Such savannahs are probably the result of man's activities, but their floras may in part be made up of plants that have persisted from former wet savannahs on the deltas of which these terraces are remains. Certain of the savannah plants have a tremendous tolerance for water-logging and desiccation.

The stabilizing function of the vegetation is, in this type of dry-land area, not as spectacular as in the following two, but still the vegetation is probably responsible for the persistence of these terrace remnants. Erosion would doubtless have destroyed them long ago if the surface were not protected by vegetation. The type of soil differs with the type of vegetation clothing the surface.

Natural levees

In the distributaries the water in the centre of the channel flows faster than that at the sides. Consequently more sediment is dropped at the sides than in the centre, and the bottom tends to build up along the sides while the centre is kept scoured clean and even deepens. As the incipient natural levees thus formed are left dry during low water in the dry season, the propagules of mangroves and other plants gain a foothold. At high water the resulting vegetation, though small and sparse, slows down the water still more and causes the deposition of more silt, building up the levee. Further silt deposition takes place during each flood season, and further establishment of vegetation during each dry season. As the level of the strip of land becomes higher, flooding may become less frequent. The composition of the vegetation changes as dry-land conditions become more prevalent. Swamp species give way to terrestrial plants. A riparian forest is formed, made up of trees well adapted to land with a rather high permanent water table. This forest, of course, carries on the usual processes of enriching the soil with organic matter and providing root channels for percolation of water and, during the now less frequent floods, brings about increased silt deposition. Its more striking function, however, is in binding the unconsolidated sediments together by its mat of roots and enabling them to resist rapid erosion during floods, thus tending to maintain the established channels of the distributaries and the integrity of the levees. Of course this is not completely effective and when channels become so blocked with silt and sand bars that they cannot carry the water, floods frequently breach the levees and inundate the intervening basins, and often succeed in altering the courses of the distributaries, or splitting them into two. This may result in abandoning the old courses and leaving undisturbed the forested levees lining them. The layer of leaf litter on the surface of the levees protects the soil from erosion by rain and these levees are consequently relatively long-lived features of the delta landscape. They are distinguished from the adjacent swamps by different, often taller, strips of forest.

On the concave sides of meanders in the distribu-

taries the levees frequently show concentric bands of vegetation of somewhat different character, often younger toward the channel. This results from accretion of younger levee material as the current cuts into the opposite levee and drops more silt on the concave side. The vegetation at once tends to occupy and stabilize these new sediments, producing the banded appearance because of its lesser age on the newer surfaces, or at least accentuating the banding already apparent in the silt deposits.

Sand ridges and flats

Along the seaward margins of deltas, in proportion to the roughness of the sea, beaches are formed and sand piled up in the form of beach ridges. Offshore bars may form and move shoreward under normal or storm wave action, until they are piled against the beach ridges and become part of them, either forming a broader ridge or a parallel series of ridges. Eventually narrow sand flats are formed, parallel with the shore. These ridges and flats tend to invade and cover the marshes or swamps or to protect them in some measure from wave erosion, or both.

The sand is very soon covered by a considerable assortment of beach plants: grasses with deep rhizomes and roots, various creepers that root at the nodes and thus form a mat anchored to the sand, and firmly rooted herbs and shrubs that tend to form a low scrub vegetation, often very dense. The sand of these beaches and ridges is very susceptible to movement by wind, as well as by water. The vegetation not only tends to resist this erosion very effectively, but even reverses the process by stopping wind-blown or water-carried sand and adding it to the surface of the ridge, often to the extent of forming small stabilized dunes. The plants making up this sort of vegetation have the ability to stand burial of their lower stems while the tips continue to grow and keep above the rising surface of the sand. Dead parts of these plants become incorporated into the sand, starting the process of soil formation. Trees in the Old World, especially *Casuarina equisetifolia*, tend to occupy these ridges, usually starting while there is still bare sand or only grass, and although slow-growing, they gradually overtop the scrub and form a very characteristic strand forest. This stabilizes the sand substratum still further.

The deltas often grow out beyond such stabilized beach ridges. Mangrove swamps, especially, tend to form in the shallow water in front of them if the turbulence is not too strong. The ridges, then, are left isolated in the swamps, and other ridges may form well out in front of the old ones, and the same processes are repeated, the vegetation in each case stabilizing the sand and collecting more of it.

Such sand ridges, at least in Old World deltas, are often cleared and planted with coconuts. Those coconut groves surrounded by swamp tend to be very satisfactory, but those just behind open beaches are less so. When the forest and scrub on beach ridges are cleared, beach erosion both by wind and waves is likely to ensue, and the sand is scattered into the swamps. Leaving an intact strip of vegetation just behind the beach will go a good way toward preventing this erosion.

Except for interference by man, and occasional natural fires, the vegetation of sand ridges is likely to persist and develop until it is destroyed by hurricanes or other storms, which, if severe enough, are able to destroy any vegetation. Even so, natural vegetation affords the most effective protection against storms. The plants have evolved in these situations and have developed very effective defences against all but the most devastating storms, and these are the ones that also destroy even the most resistant works of man in such situations.

TROPICAL VERSUS TEMPERATE ZONE DELTAS

Basically there seems to be little difference between the delta-forming processes in tropical and those in temperate zones. Perhaps the difference in vegetation is more fundamental than that in sedimentation processes, except as these are influenced by vegetation.

The outstanding vegetational difference is that the dense, herbaceous salt-marsh vegetation of temperate deltas is mostly replaced by mangrove swamp in the tropics. Mangrove-swamp vegetation is coarser, less dense, woody, and far taller. It does not bind the sediments with as fine a mesh as does salt marsh, but seems to bind them effectively, nevertheless.

While the ultimate vegetation or temperate deltas may also be forest, the early stages in succession are herbaceous vegetation. In the tropics, probably because of the special viviparous dispersal mechanisms evolved by various mangrove species, the earliest pioneer stage is forest made up of one of several species of trees that are adapted to life in salt of brackish water, commonly called mangroves. The seeds of many of these germinate while the fruits are still hanging on the trees. The young plants are then dropped into the water and carried by the currents to mud flats or other appropriate substrata. Already developing, these large seedlings are ready to take hold at once and can colonize areas where seeds would be washed off before being able to germinate and gain attachment. Thus the expected herbaceous pioneer successional stages are ordinarily skipped and a relatively stable forest stage is established from the beginning.

Mangrove-swamp forest, especially where a number of species with different root systems are involved, is a vegetation remarkably well adapted to trapping silt and resisting ordinary erosion. Hurricanes frequently succeed in destroying areas of mangrove swamp, but these swamps are seldom very seriously affected by ordinary flood-waters. Whether or not mangrove swamp is a more effective silt collector than temperate salt

marsh has not, to the best of my knowledge, been determined. Both, when well established, are resistant to the types of erosion to which they are normally subjected. Beyond this there is probably no adequate way to compare them in this respect.

An outstanding difference between tropical and most temperate deltas is that the tropical ones are flooded to enormously greater depths and for much greater lengths of time than is usual in the temperate zone. It seems quite possible that herbaceous vegetation might deteriorate from reduced photosynthesis during such long complete inundation, and that the much greater stature of the mangrove swamps serves as an adaptation to overcome this handicap.

The fact that peat swamps in tropical deltas replace the freshwater marshes of temperate deltas to a large extent may simply reflect the fact that tropical floras are woody to a far greater extent than are temperate ones, and thus these habitats are far more likely to be colonized by woody plants than by herbaceous ones; also in a diverse woody flora there are more likely to be successful competitors among the tree species than in the tree-impoverished temperate floras.

Résumé

La végétation, agent géologique de la formation des deltas dans la zone tropicale (F. R. Fosberg)

Les deltas sont constitués par des sédiments fins, généralement sans liaison, saturés d'eau et intrinsèquement instables. Même lorsqu'ils sont encore submergés, ces sédiments tendent à se couvrir d'une végétation aquatique enracinée qui exerce un certain effet stabilisateur. Dès que le dépôt est assez abondant pour être découvert quand les eaux sont basses, des plantes aquatiques émergentes et même des plantes terrestres y prennent pied. A mesure qu'elles se multiplient pour former soit une végétation de marécage, soit, si le sol reste à découvert de façon relativement continue, un tapis d'herbe, ou de plantes rampantes, ou des broussailles qui fixent le sable, elles contribuent considérablement à stabiliser les sédiments. Leurs parties mortes viennent en outre s'ajouter aux éléments organiques que contiennent les sédiments eux-mêmes. A l'intérieur des deltas sablonneux, ces détritus végétaux forment de profondes couches de tourbe. Le delta constitue ainsi un système écologique en état d'équilibre dynamique entre, d'une part, les diverses forces d'alluvionnement et de destruction qu'exercent les courants fluviaux et les vagues marines, ainsi que les vents et les orages, et, d'autre part, la tendance des plantes à coloniser et à stabiliser toutes les surfaces terrestres, submergées ou émergées, et même la surface de l'eau, et à ajouter des matières organiques aux sédiments et aux sols ainsi formés. La végétation naturelle des sols deltaïques protège très efficacement les dépôts de sédiments instables ainsi formés contre toutes les formes d'érosion et ménage d'immenses surfaces de frottement qui, ralentissant le vent et l'eau, les amènent à déposer les sédiments qu'ils contiennent, ce qui a pour effet de renforcer les deltas.

Discussion

V. J. Chapman. (1) Could Dr. Fosberg please elucidate his final paragraph on peat swamps?

(2) I would like to make some comments on Dr. Fosberg's paper. He refers to various physiographic features to which I would like to add "shell banks", which are an important feature of mangrove swamps in New Zealand and which are indeed necessary for mangrove vegetation if it is to develop. He also refers to the problem of meandering creeks. Such meandering creeks can be seen in certain salt marshes of temperate areas, particularly those dominated by rice grass (*Spartina*). I believe these creeks are determined by the chance distribution of the plants. Once some plants have been established they determine where the new runnels will develop. In mangrove vegetation I think the same phenomenon may occur—indeed in Malaya one can see the spread of mangrove seedlings along existing creek outlets and isolated plants on the outside may well determine the occurrence of secondary runnels.

Turning now to Dr. Fosberg's new material, there are two matters on which I would like to make some observations. The first item is the difference between tropical mangrove swamps and temperate herbaceous salt-marsh vegetation. Salt-marsh species do occur in the tropics—we have just seen slides of them in Ceylon from Professor Abeywickrama. I believe these herbaceous salt-marsh plants are essentially sun plants—they require light and will not grow in the shade—some work we have done at Auckland suggests this. Mangroves cast a fair shade and I believe this is sufficient to stop them appearing as undergrowth. At the rear of the mangroves where the salinity is too high for mangroves or the water

supply is inadequate, there you will find typical salt-marsh species, as I have seen them in Ceylon, growing in the open and forming a salt marsh.

The other matter is that I do not think I can go along with Dr. Fosberg when he suggests that peat swamps are more abundant in tropical deltas than in temperate deltas. I believe it is more a matter of the conditions. Given these then I believe peat will form under either circumstance. I have in mind the peat soils of salt marshes in south-western Ireland and the extensive series along the New England coast of North America. You certainly can get peat formed under mangrove conditions but it is usually in places where there is not a great deal of silt coming down. The mangrove swamps in Kingston Harbour, Jamaica, are built up of a really compact peat. I believe, therefore, that there is not this distinction between salt marshes and mangrove swamps.

F. R. Fosberg. In certain tropical deltas, particularly in Malaysia, in basins that are closed off from the sea by broad sand ridges and not subject to flooding by silt-laden water, and where the nutrient status is apparently very low, swamps occur in which the remains of trees do not fully decompose as long as they remain waterlogged, and a peat accumulation takes place, corresponding to a temperate or cold zone bog, which may have a dome-shaped surface and a thickness of purely organic material of as much as 40 ft. Peat accumulation is also known under marshes of the tropical reed *Phragmites karka*.

From Dr. Chapman's description of the "shell banks" they would seem to be beach ridges, comparable to the more common sand ridges described in the paper.

In the version of my paper that has been distributed, I suggested that the origin of the tightly meandering nature of the delta channels and salt-marsh channels is not clear to me. One of my geologist reviewers assured me that it is clear enough, that it is due only to the extremely low gradient in elevation of these channels. Now Dr. Chapman suggests that it is due to chance distribution of plants. It is still unclear to me.

I am glad to see that Dr. Chapman agrees with one of my suggestions, that herbaceous salt-marsh species may be shaded out in competition with trees.

I am quite aware that peat is formed in temperate zone salt marshes. I was not contrasting presence or absence of peat, but swamps, with trees dominant, against marshes, with herbs dominant. Of course, this is not a complete contrast, as there are salt marshes in the tropics and swamps in temperate deltas; I am only indicating the more usual conditions. And I will agree that mangrove peat does exist, but the peat swamps I refer to are freshwater peat swamps.

Begum. B. Tamjida. In what condition do the fruits or seeds of mangrove germinate while hanging on the trees.

F. R. Fosberg. The seed actually germinates within the fruit when the fruit is mature, and an enlarged radicle grows out, hanging downward. At a certain stage it becomes heavy enough to pull its tiny cotyledon leaves free from the fruit and falls into the water or mud beneath the tree.

M. Ahmad. Dr. Fosberg put forward the suggestion that during the establishment of mangrove forests, herbs are gradually eliminated as a result of the shade produced by trees.

I would say that, although it is true that there are some sun-loving herbs and shrubs which are gradually eliminated from an area once trees are established, it does not seem advisable to generalize that herbs are replaced by trees as a result of shading by trees.

In the waterlogged areas of the northern part of this province the trees find it difficult to survive, but the grasses and reeds abound. This may be due to a better resistance offered by the underground parts of grasses and reeds as compared to the roots of trees. Further, the grasses and reeds have a much shorter life cycle than trees and therefore they are able to produce a much larger number of bio-types which can be selected by the environment. Hence the annuals and biennials have a better chance of colonization of areas than the trees.

Aperçu sur la végétation occupant les alluvions récentes de la partie méridionale de l'Indochine

M. Schmid

Le delta du Mékong, qui constitue une grande partie de l'Indochine méridionale, comprend, suivant les variations du régime des inondations et suivant la qualité des sédiments, plusieurs zones bien distinctes.

L'extrême sud, du fait de l'instabilité des dépôts et de la pénétration permanente des eaux marines, est occupé par une vaste mangrove que le Service forestier a commencé à aménager en raison de l'intérêt qu'elle présente pour la production du charbon de bois, principal combustible utilisé au Viêt-nam.

Sur les alluvions mieux stabilisées, les cultures s'étendent largement. Les terres renfermant des sulfures s'oxydant en sulfates acides, dont la superficie à l'ouest de Saigon et dans la région de Rach Gia est considérable, sont occupées toutefois par des groupements herbacés comprenant essentiellement des Cypéracées (*Elaeocharis*, *Lepironia*...) ou, localement, par des fourrés (*Annona*...), le coût des travaux nécessaires pour leur mise en valeur apparaissant généralement hors de proportion avec la valeur des récoltes que l'on peut espérer obtenir[1].

Aux confins du delta et des régions montagneuses ou à l'intérieur de ces dernières existent des cuvettes d'étendue variable où, soit en raison des conditions physiques (irrégularité ou trop forte amplitude des inondations), soit en raison des conditions de peuplement (populations trop clairsemées, modes de vie), la végétation naturelle a été mieux conservée. La plus importante de ces cuvettes est sans conteste la dépression du Tonlé Sap au Cambodge, qui, largement ouverte sur le delta, constitue pour le Mékong un réservoir de régulation. Au Viêt-nam, en bordure de la Srépok, du Donnaï, de la Lagna... les alluvions constituent localement, souvent en arrière de coulées de basalte qui ont barré le cours des rivières, de petites plaines de quelques dizaines de milliers d'hectares dont l'étude présente également un vif intérêt, en raison des fortes variations que présentent, sur de faibles distances, les conditions hydrauliques et pédologiques. C'est à l'examen des principaux types de groupement occupant ces zones deltaïques marginales que mon exposé sera consacré.

Les principales observations que j'ai pu faire sur la structure et sur la composition de la végétation dans la cuvette du Tonlé Sap et des plaines comprises dans la zone montagneuse seront présentées séparément.

LA VÉGÉTATION OCCUPANT LES TERRES PÉRIODIQUEMENT INONDÉES DE LA CUVETTE DU TONLÉ SAP

La superficie du Grand Lac qui occupe le centre de la dépression est de 2 700 km² en étiage; en période de crue, les eaux s'étendent approximativement sur 10 000 km². Le *p*H moyen des eaux du lac (lit mineur) est supérieur à 7; celui des eaux des canaux naturels (preks) est sensiblement plus bas (*p*H voisin de 6, en novembre, dans la région de Siem Reap).

La zone du lac, recouverte en permanence par les eaux, est à peu près dépourvue de végétation, exception faite des algues entrant dans la constitution du plancton. Cependant, dans les étangs d'étendue relativement faible que l'on observe un peu en retrait des berges du lac et dans les preks qui les relient à ce dernier ou vont se perdre dans la forêt, les plantes aquatiques sont généralement très abondantes. Il semble que l'absence de végétation dans les eaux du lac soit due essentiellement à l'agitation des eaux, sur lesquelles les vagues soulevées par les vents de mousson rendent souvent la navigation difficile. Elle pourrait être due également à la forte turbidité des eaux consécutive à cette agitation en période d'étiage, la profondeur moyenne du lac n'excédant pas alors un mètre.

1. Sur la mangrove occupant la partie méridionale du delta, on lira avec intérêt le travail de Moquillon (archives du Service forestier de l'Indochine, 1945-1950). Sur la végétation occupant les alluvions renfermant des sulfures ou des chlorures, on trouvera des renseignements dans les archives de l'Office du riz à Saigon et dans le travail de Vu van Cuong (diplôme d'études supérieures présenté à l'Université de Saigon, 1960).

Les terres s'étendant entre le lac et les limites extrêmes de la zone d'inondation sont en majeure partie occupées par ce qu'on appelle la « forêt inondée », complexe de forêt proprement dite et de fourrés. En bordure du lac, par places, on observe cependant des formations herbacées. A l'intérieur de la forêt même, on trouve des prairies disposées comme en chapelets parallèlement aux berges du lac. Enfin, en bordure du lit majeur, la prairie semi-aquatique présente parfois une grande extension; mais le développement des cultures dans cette zone ne permet pas d'en apprécier de manière certaine l'étendue originelle.

Les conditions qui régissent cette distribution particulière des formations ligneuses et des formations herbacées semblent être principalement d'ordre physique : les premières occupent les zones où les sédiments sont relativement consolidés et où l'alluvionnement est faible; les secondes, les zones où l'alluvionnement se poursuit. En outre, les formations herbacées existent là où, pour des raisons topographiques, les terres se ressuient mal ou restent sous les eaux longtemps après la décrue. Le degré d'agitation des eaux (vagues, courants) conditionne secondairement la distribution de différents groupements.

L'influence des variations de la teneur des eaux en éléments solubles ou des variations de leur *p*H n'apparaît pas nettement; mais, dans ce domaine, mes moyens d'investigation n'étaient pas suffisants pour que je puisse formuler une opinion réellement fondée.

Avant d'aborder l'étude des principaux groupements, il convient de faire quelques remarques générales sur la physiologie et les affinités floristiques de leurs constituants.

Les cycles de développement des végétaux sont liés davantage au régime des crues qu'au régime climatique.

De ce point de vue, on peut distinguer plusieurs catégories d'espèces :

Les arbres et beaucoup de lianes conservent des feuilles toute l'année, les houppiers, souvent assez denses et en forme de dôme, se déployant au niveau maximum atteint par les eaux ou légèrement au-dessus. Les floraisons sont nombreuses en mai-juin, vers la fin de la période de décrue. Plusieurs lianes (*Acacia*) et quelques arbres (*Drypetes*) fleurissent cependant au moment où les eaux sont hautes (novembre).

Parmi les arbrisseaux, il est beaucoup d'espèces qui, complètement recouvertes par les eaux en période de crue, perdent alors leurs feuilles (*Ficus*, *Morinda*, *Vitex*...). Les jeunes feuilles apparaissent dès le retrait des eaux (janvier) et les floraisons ont lieu en période d'étiage (juin). Plusieurs de ces arbrisseaux ont des feuilles profondément lobées (*Morinda*, *Grewia*). Cependant, *Sesbania paludosa* présente son développement maximum au moment des hautes eaux, au-dessus desquelles se dressent les ramifications portant feuilles et fleurs. D'autres espèces croissant en bordure de la zone inondée, là où les eaux ne sont jamais très profondes et se retirent de bonne heure, sont sempervirentes (*Hymenocardia*). Enfin, *Crataeva nurvala*, colonisateur des laisses alluviales qui, en période de crue, constituent de hauts fonds, présente un comportement très particulier : c'est la seule espèce qui, sans être jamais complètement noyée, perde ses feuilles en période de hautes eaux : ses ramifications complètement dépouillées donnent alors l'impression que l'arbuste est mort, son identification devenant facile à forte distance.

Parmi les plantes herbacées, on peut distinguer les végétaux aquatiques flottants ou faiblement fixés au fond (*Utricularia*, *Eichhornia*), les végétaux aquatiques originellement fixés produisant des stolons qui s'allongent au fur et à mesure de la montée des eaux (Graminées, *Polygonum*), dont les floraisons ont lieu surtout en automne et qui disparaissent en période d'étiage, et les herbes dressées, semi-aquatiques (Graminées, *Scirpus*, *Impatiens*, *Aeschynomene*, *Sphenoclea*...) ou n'apparaissant que sur des terres plus ou moins ressuyées (Cyperacées, *Sorghum*, Composées), qui ne fleurissent qu'en période d'étiage [1].

Beaucoup des espèces du dernier groupe sont des thérophytes, certaines ayant un cycle de développement très court et ne s'observant que sur les terres découvertes pendant une brève durée (*Echinolytrum*, *Fimbristylis*, *Cyperus*, *Mollugo*...) [2].

La flore, dans l'ensemble, n'a pas la richesse de celle des forêts tropicales. Dans le groupe des végétaux herbacés, on notera la prépondérance écrasante des Graminées sur les Cypéracées, ces dernières étant représentées par un assez grand nombre d'espèces, mais ne jouant dans la plupart des groupements qu'un rôle secondaire. Il est possible qu'il existe une relation entre ce fait et le caractère général relativement basique du milieu (*p*H des eaux du lac compris entre 7 et 8).

Dans le groupe des végétaux ligneux, on notera l'importance des Légumineuses qui sont représentées surtout par des lianes (*Dalbergia*, *Acacia*) et comprennent aussi de grands arbres (*Cynometra*, *Albizzia*, *Crudia*), qui sont plutôt, toutefois, des essences de berges, et un arbuste particulièrement abondant, *Sesbania paludosa*. Les Euphorbiacées sont nombreuses, jouant un rôle souvent prépondérant dans les fourrés (*Croton*, *Hymenocardia*, *Phyllanthus*...), mais représentées aussi dans la strate arborée (*Coccoceras*, *Drypetes*). Les Combrétacées comptent au moins deux espèces importantes, un *Terminalia* et un *Combretum* lianoïde. Les Myrtacées ne sont représentées que par un *Barringtonia*, d'ailleurs très abondant. Les Lythracées sont absentes.

D'une manière générale, il s'agit d'espèces liées étroitement au biotope considéré. Il semble que les véritables endémiques soient peu nombreuses; mais les aires

1. Quelques graminées dressées ou subdressées fleurissent en période de hautes eaux (*Saccharum*, *Hermarthria*), mais il s'agit là plutôt d'espèces ripicoles.
2. Plusieurs de ces espèces s'observent principalement sur des alluvions de texture assez grossière.

de plusieurs lianes et arbutes apparaissent en Indochine limitées à cette zone.

Bornant là ces généralités, je donnerai maintenant un aperçu sur la répartition, la structure et la composition des principaux groupements.

La forêt inondée

C'est une formation comprenant essentiellement une strate supérieure pouvant se situer entre 8 et 20 mètres, souvent ouverte, les contours des houppiers étant grossièrement circulaires, et une strate inférieure arbustive, à structure de fourré, dont la densité varie avec celle de la strate supérieure. Les lianes sont abondantes, surtout en bordure du lac et des preks. Il n'y a pas d'épiphytes.

Les arbres ont des troncs relativement courts, les plus gros approchant d'un mètre de diamètre; les houppiers sont très ramifiés.

Cette formation s'observe sur les alluvions stabilisées, là où l'amplitude annuelle des variations de niveau de l'eau est de l'ordre de 5 à 8 mètres. L'exploitation pour la production de bois de feu a beaucoup dégradé les peuplements et diminué l'abondance relative de certaines espèces (*Terminalia*), voire entraîné leur disparition (*Homalium*). C'est à l'est de Battambang et au sud de Kompong Tom que j'ai observé les peuplements les mieux conservés. C'est là, d'ailleurs, que la largeur de la ceinture forestière est la plus grande.

La flore varie peu d'un secteur à l'autre, tout au moins dans ses constituants fondamentaux : certaines espèces, toutefois, s'observent plus particulièrement en lisière, alors que d'autres jouent un rôle beaucoup plus important à l'intérieur des massifs. Ayant effectué mes prospections principalement en bateau, en période de crue, les espèces de lisière me sont les mieux connues.

Arbres

a) Espèces les plus communes :

En lisière, aussi bien en bordure du lac (eaux agitées) que le long des preks (eaux calmes) :
Barringtonia acutangula.
Diospyros sp.[1]
Coccoceras anisopodum : espèce de plus grande taille, un peu moins abondante que les deux précédentes.

En bordure ou sur les hauts-fonds des bengs enherbés :
Xanthophyllum glaucum : essence atteignant d'assez fortes dimensions, en peuplements très dispersés.

A l'intérieur des massifs :
Terminalia cambodiana.

b) Espèces moins communes, abondantes seulement dans certains secteurs ou très dispersées :

Cynometra ramiflora : arbre atteignant une vingtaine de mètres, observé seulement en bordure du Stung de Pursat ou des preks du voisinage.
Albizzia lebekkoides : serait plutôt une essence de berge, s'observant en bordure des stungs, sur des terres assez filtrantes ou ne demeurant pas très longtemps sous les eaux.
Crudia chrysanthera : grand arbre (30 mètres) observé seulement sur des laisses alluviales un peu en aval des bouches de Cchnok Tru.
Drypetes thorelii : petit arbre très finement branchu, assez commun en bordure des preks des secteurs N.-O.
Homalium brevidens : essence de l'intérieur des massifs, bien connue des forestiers, mais paraissant devenue rarissime.
Elaeocarpus madopetalus : petit arbre, à l'intérieur des massifs ou sur les berges, surtout au voisinage des villages, en peuplements très dispersés.
Garcinia sp. : essence à rameaux très allongés, presque lianescents, observée au voisinage des bouches de Cchnok Tru.
Hydnocarpus sp. (berges du stung Seng).
Bambusa arundinacea : s'observe parfois sur les berges des grands preks et des stungs, au voisinage des villages.

Arbrisseaux

Voir ci-dessous « Les fourrés ».

Lianes

En lisière, sur le lac ou le long des preks :

Combretum trifoliatum.
Dalbergia entadoides : surtout le long des preks.
Acacia spiralis : s'observant aussi à l'intérieur des massifs, là surtout où la végétation a été dégradée.
Hiptage triacantha.
Styxis harmandiana.
Uvaria pierrei : abondant dans le secteur du stung de Pursat, s'observant aussi dans les zones où la végétation a été dégradée.
Ipomaea chryseides : en bordure des grands preks, plus abondant là où la végétation a été dégradée.
Calamus sp. : peu commun.
Cudrania cambodiana : berges.

Les fourrés

Le fourré est une formation secondaire de substitution à la forêt.

Haut de quelques mètres, il est complètement noyé en période de crue. Il s'étend toutefois à des zones où la montée des eaux est faible; les ramifications supérieures des arbustes, constamment émergées, conservent alors leurs feuilles toute l'année.

La structure du fourré est très dense et confuse, les lianes et les arbrisseaux sarmenteux y jouant un rôle important.

1. Espèce à rapprocher de *D. bejaudii*, mais à fruits plus petits, peut-être encore non décrite.

Arbrisseaux

a) Espèces les plus communes :

Phyllanthus reticulatus.
Croton Krabas.
Schoutenia godefroyana : parfois lianoïde, assez répandu également en secteur boisé, en bordure des preks.
Croton cf. *C. mekongensis* : répandu partout, mais moins commun que les espèces précitées.
Morinda persicaefolia, *Ficus heterophylla*, *Vitex holaodenon*, *Grewia sinuata*... s'observant seulement là où le fourré est entièrement et longuement recouvert par les eaux en période de crue, principalement en bordure des laisses alluviales (bouches de Cchnok Tru) et pouvant constituer des groupements de première installation.
Crateva nurvala, espèce pionnière sur les laisses alluviales, s'observant principalement dans les zones où le courant de crue et le courant de décrue sont rapides.

b) Autres espèces, moins caractéristiques, communes surtout en bordure de la zone d'inondation :

Hymenocardia wallichiana : pouvant atteindre les dimensions d'un petit arbre.
Gmelina sp. : souvent sarmenteux.
Samandura harmandii : petit arbre sur les berges du stung Seng.
Clerodendron longisepalum : berges du stung Seng.
Desmodium clovisii : zones à végétation très dégradée.
Phyllanthus spp.

Lianes

Parmi les espèces déjà mentionnées à propos de la forêt, beaucoup sont communes dans les fourrés (*Combretum*, *Dalbergia*, *Acacia*, *Ipomaea*...).

Tetracera sarmentosa et *Streptocaulon Kleinii* s'observent surtout là où la végétation a été très dégradée.

Groupements ligno-herbacés ou herbacés subaquatiques

Ces groupements s'observent soit en bordure du lac, en avant de la forêt inondée, sur des laisses alluviales longuement noyées, soit en bordure des bengs qu'ils peuvent occuper entièrement s'ils s'assèchent aux basses eaux. Ils se succèdent parfois sur le même terrain dans le temps, l'un des groupements présentant son développement maximum en période de crue, l'autre en période d'étiage.

a) A développement maximum aux hautes eaux (de longs stolons se développent alors, dans le cas des espèces herbacées, supportant des tiges aériennes dressées, assez courtes) :

Groupement à *Echinochloa stagnina* et *Sesbania paludosa*, colonisant les laisses alluviales instables, en eau agitée.
Groupement à *Sacciolepis myuros* (espèces dominantes), *Paspalum* cf. *P. scrobiculatum*... colonisant les bengs.
Groupements à *Chamaeraphis minuta*, à *Oryza rufipogon*... assez localisés, dans les bengs où l'eau séjourne longtemps, parfois en bordure du lac, là où les eaux sont relativement calmes (berges nord du Petit Lac).
Groupements à *Polygonum barbatum*, *Achyranthes aquatica*, *Ipomaea aquatica*, *Commelina salicifolia*... s'observant surtout en eaux calmes (preks), parfois associés à une végétation franchement aquatique (*Eichhornia*).
Jussiaea repens, associée à un *Polygonum*, s'observe localement, le long de preks étroits, à assez grande distance du lac.

b) A développement maximum en eaux peu profondes (ces groupements colonisent, en bordure du lac ou des grands preks, des laisses alluviales encore mal consolidées ou des terres de berges) :

Groupement à *Hemarthria longiflora* sur les berges basses.
Groupements à *Leersia hexandra*, *Sphenoclaea zeylanica*, *Aeschycnomene aspera*, *Melochia* sp., *Jussiaea*, *Polygonum*... pouvant coloniser des laisses alluviales noyées sous une faible épaisseur d'eau.
Groupement à *Vossia cuspidata*... (en aval des bouches de Cchnok Tru).

c) Groupements de type intermédiaire entre les deux précédents (berges basses surtout) :

Groupements à *Brachiaria mutica*, *Leptochloa sinensis*... (berges basses à une assez grande distance du lac).

d) Groupements propres aux zones où l'eau en période d'étiage a tendance à stagner :

Groupements à Cypéracées (*Scirpus*...), *Leersia*...

Groupements aquatiques

Ces groupements s'observent surtout en eaux calmes. Les inflorescences apparaissent aux hautes eaux.

a) En bordure du lac :

Groupement à *Eichhornia* (*Sesbania paludosa*, *Polygonum barbatum*... lui sont souvent associés).
Groupement à *Ceratophyllum demersum*, constamment immergé. (*Ceratophyllum demersum* peut s'observer en eaux un peu agitées aussi bien qu'en eaux calmes, mais assez claires. *Ceratopteris thalictroides* lui est parfois associé, dans les eaux calmes.)

b) Le long des preks et dans les bengs :

Groupement à *Utricularia flexuosa*, *Ceratophyllum*...
Groupement à *Nelumbo speciosum*... (peu commun, à assez grande distance du lac.)

Groupements anthropophiles

Ces groupements s'observent aux alentours des villages, sur les terres encore humides ou complètement ressuyées aux basses eaux.

Prairie (structure assez lâche) à Composées (*Eclipta alba*, *Grangea maderaspatana*, *Sphaeranthus* sp.), Cyperacées (*Cyperus*, *Fimbristylis*, *Echinolytrum*), *Coldenia procumbens*, *Mollugo oppositifolia*, *Cleome viscosa*... s'observant principalement sur les terres complètement découvertes mais se ressuyant mal en période d'étiage.

Savane à *Sorghum affine* sur les alluvions riches, drainant bien en période d'étiage (terres cultivées).

Groupement à *Quisqualis densiflora* dans les zones où le courant de crue ou de décrue est assez fort (voisinage des ouvrages d'art).

Groupements de type intermédiaire entre les deux précédents, à structure souvent confuse, comprenant des arbrisseaux (cf. végétation des fourrés et quelques espèces herbacées dressées ou volubiles, *Xanthium strumarium*, *Cardiospermum halicacabum*...).

LA VÉGÉTATION DES PLAINES ALLUVIALES JALONNANT LES COURS DES GRANDES RIVIÈRES DU SUD VIÊT-NAM

Les conditions diffèrent ici de celles qui se trouvent réalisées dans la cuvette du Tonlé Sap en ce que la montée des eaux en période de crue est beaucoup plus rapide et moins régulière. En outre, les alluvions sont plus abondantes et leur granulométrie plus variable, des lits de sable grossier se superposant parfois à des niveaux argileux. Enfin, les eaux des rivières qui drainent les hauts plateaux du Viêt-nam méridional sont plus acides que celles du Mékong et du stung de Battambang, qui jouent un rôle majeur dans l'alimentation du Tonlé Sap.

La végétation occupant les plaines alluviales du Sud Viêt-nam est essentiellement herbacée, prenant en général en saison d'étiage la forme d'une prairie très dense là où les dépôts sont argileux et où la durée de la période de submersion est longue, prenant la forme d'une savane herbeuse ou parsemée de quelques arbres là où les dépôts présentent un caractère plus limoneux et où les inondations sont relativement brèves. Les terres de berges, limono-sableuses et recouvertes seulement par les eaux d'une manière épisodique, sont occupées soit par des savanes arborées, soit par des forêts.

Du point de vue physiologique comme du point de vue floristique, les prairies se rapprochent des groupements herbacés subaquatiques du Tonlé Sap : en particulier, c'est en période de hautes eaux qu'elles présentent leur développement maximal, de longs stolons (portant les tiges qui vont donner des inflorescences) apparaissant alors. *Sesbania paludosa*, souvent associé aux hautes Graminées, fleurit à ce moment. L'abondance des arbres paraît inversement proportionnelle à la durée de la période d'inondation, proportionnelle à la profondeur des horizons se ressuyant bien, cela indépendamment de la granulométrie des sédiments. Il existe toutefois, surtout en bordure des plaines, là où des affleurements phréatiques maintiennent une humidité quasi permanente, des groupements ligneux à pneumatophores ou racines-échasses appartenant au groupe des forêts de marais et non au groupe des forêts inondées.

La flore des prairies est essentiellement graminéenne, comprenant la plupart des Panicées et Oryzées signalées dans la cuvette du Tonlé Sap. Les espèces n'appartenant pas à la famille des Graminées paraissent moins nombreuses qu'au Cambodge, en tout cas n'y jouent pas un rôle aussi important.

La flore des savanes comprend surtout des Andropogonées, Saccharées (*Sclerostachya*, *Saccharum*) sur les alluvions limono-argileuses, *Vetiveria*, *Themeda* sur les alluvions moins fines, surtout là où les inondations sont de courte durée. *Panicum repens* forme par places des prairies sur terres assez légères; *Phragmites karka* s'observe sur des alluvions assez fines mais se ressuyant bien en période d'étiage.

Les arbres comprennent des espèces liées assez étroitement à un biotope déterminé, *Adina*, *Stephegyne*, *Bombax*, dans les zones à *Saccharum* ou *Phragmites*, *Dipterocarpus alatus*, *Fagraea*, *Lagerstroemia*, *Bombax*, dans les groupements ripicoles. On observe aussi quelques espèces banales dans les savanes sur sols ferrallitiques, *Careya*, *Bauhinia*. Les floraisons ont lieu principalement aux basses eaux.

La végétation purement aquatique n'offre rien d'original par rapport à celle du Cambodge (*Utriculara flexuosa*, *Nelumbo*...).

Je ne m'étendrai pas davantage sur la composition et sur la répartition des différents groupements, ayant traité la question assez en détail dans un travail précédent [1].

CONCLUSION

La végétation occupant les plaines alluviales situées en bordure ou au voisinage du delta du Mékong, assez bien conservée dans son ensemble, présente une grande diversité de composition et de structure, la flore des terrains périodiquement inondés mais non marécageux apparaissant dans son ensemble très spécialisée mais assez pauvre.

Les observations faites tant au Cambodge qu'au Viêt-nam font ressortir l'influence primordiale du régime des inondations et des modalités d'alluvionnement sur la distribution des groupements. Les différences constatées entre la végétation des petites plaines inscrites dans un relief montagneux et celle qui occuppe la vaste cuvette du Tonlé Sap s'expliquent principalement de ce fait; on peut admettre toutefois que l'exiguïté relative des plaines étudiées au Viêt-nam (30 à 50 000 hectares) et leur isolement sont partiellement responsables de ces différences. La flore des plaines du Viêt-nam comprend une majorité d'espèces à large distribution en Asie, voire pantropicales. La flore du Tonlé Sap est

1. *Contribution à la connaissance de la végétation du Viêt-nam : le massif sud-annamitique et les régions limitrophes*, thèse, Faculté des sciences d'Orsay, 1962.

plus originale, du moins dans ses constituants ligneux. Mais nous connaissons peu de choses sur les modalités de dissémination des espèces (zoochorie, hydrochorie ...).

Par rapport aux forêts ou prairies occupant les terrains marécageux, on notera l'absence (ou le caractère exceptionnel) de pneumatophores chez les espèces ligneuses, le rôle important joué par les herbes stolonifères, la pauvreté de la flore. De ce dernier point de vue, le contraste entre la richesse floristique des prairies occupant les dépressions mal drainées et la pauvreté des groupements herbacés observés sur les alluvions récentes mérite d'être souligné.

L'absence d'épiphytes dans la « forêt inondée » peut surprendre, alors que les épiphytes sont généralement très abondants dans les forêts limnicoles. La sécheresse relative du climat qui règne sur la cuvette cambodgienne en est vraisemblablement la cause. Ne disposant encore d'aucune donnée sur les variations du degré hygrométrique au cours de l'année dans la dépression du Tonlé Sap, je ne puis formuler sur ce point d'opinion précise.

L'intérêt de la « forêt inondée » pour la production du charbon de bois est connu depuis longtemps et son exploitation très poussée entre 1940 et 1945 explique l'état de dégradation avancée d'une grande partie des peuplements. Nombre d'espèces rejetant de souche (*Terminalia cambodiana* ...), il est néanmoins probable qu'en de nombreux secteurs les principaux constituants de la végétation climacique se sont partiellement maintenus.

La composition des groupements herbacés a vraisemblablement peu varié. Leur intérêt principal, comme d'ailleurs celui de la forêt, réside dans le rôle qu'ils jouent dans la biologie de la macrofaune, dont la richesse est exceptionnelle. D'une part, la végétation alimente de ses débris un plancton abondant; d'autre part, les stolons et les rameaux noyés servent de support aux pontes. D'après les observations de d'Aubenton [1], il ne semble pas, cependant, que beaucoup de poissons pénètrent dans les massifs forestiers à grande distance des berges.

En dehors de leur intérêt économique, la sensibilité des groupements aux variations des conditions d'humidité et de sol en justifie l'étude attentive; l'examen de leur répartition apporte, en effet, de précieux renseignements sur les variations dans l'espace des conditions hydrologiques et sédimentologiques, rendant par là grand service dans la prospection agroloqique des plaines alluviales dont, en Indochine, de vastes secteurs demeurent encore inexploités.

1. Compte rendu des observations faites au cours d'une mission effectuée en 1961-1963 pour le Comité du Mékong.

Summary

Brief description of the vegetation occupying the recent alluvia of southern Indo-China (M. Schmid)

The vegetation occupying the alluvial plains along or near the Mekong delta—which is, on the whole, in a reasonably good state of conservation—exhibits great diversities of composition and structure, with the flora of the areas, which are periodically inundated but not marshy, emerging generally as highly specialized but rather poor.

The observations effected while in Cambodia and in Viet-Nam underline the leading part played by the inundation regimen and the alluviation determinants on the distribution of the communities. They are the main reason for the differences noted between the vegetation of the small plains inset in mountain areas and that of the vast Tonlé Sap basin, though it is conceivable that the relative exiguity and the isolation of the plain lands studied in Viet-Nam (30 to 50,000 hectares) are partially responsible. The lowland flora of Viet-Nam consists in the main of species widely distributed in Asia or even throughout the tropics, whereas that of the Tonlé Sap appears to be much more individual, particularly as regards its woody components. However, we know little about the mechanisms of species distribution (by animal vectors, by water, etc.).

It will be observed that, compared to forest or grasslands on marshy soils, pneumatophores are missing or unusual among the woody species, stoloniferous herbs are an important element and the flora is poor. With regard to this last point, it is worth stressing the contrast between the floristic wealth of the grasslands in the ill-drained depressions and the poverty of the herbaceous communities studied on the recent alluvia.

Some surprise may be felt at the absence from the "flood forest" of the epiphytes, usually extremely abundant in riparian woodlands. The reason is probably the relative dryness of the climate in the Cambodian basin. As I still have no data on the year-long variations in the hygrometric level for the Tonlé Sap depression, I can form no exact opinion on this point. It would seem that the intense dry season evaporation is not enough to maintain a suitable degree of atmospheric humidity in the neighbourhood of the water surface for the development of epiphytes. While other factors may play a part, I have not determined them.

The value of the "flood forest" for charcoal manufacture has long been known and the heavy felling for

the purpose between 1940 and 1945 explains the advanced state of degradation of much of it. However, as the stumps of many species (*Terminalia*, *Cambodiana*, etc.), put out new shoots, there is a probability that in many sectors the main elements of the climax vegetation have partly held their ground.

There seems to have been little change in the composition of the herb populations. Like the forest itself, they are mainly important for the part they play in the biology of the exceptionally rich macrofauna. To begin with, the debris from the vegetation provides food for an abundance of plankton; in addition, the submerged stolons and branches provide an anchorage for spawn. However, d'Aubenton's observations[1] suggest that few species penetrate into the forest stands to any great distance from the river banks.

Apart from their economic interest, the sensitiveness of the plant communities to variations in the humidity and soil conditions makes them worth close study: their distribution provides valuable information on the spatial variations in hydrological and sedimentological conditions, and thus is of immense help for the agrological prospection of the alluvial plains, of which vast areas in Indo-China are still unexploited.

1. Report of observations effected during a mission for the Mekong Committee in 1961-1963.

Influence of forests on the soil and microclimate in the humid tropics

Q. Ghani

The humid region of the tropics is generally confined to the central zone of the world, lying within a few degrees north and south of the Equator. East Pakistan, geographically speaking, is on the border-line of the tropical zone and even extends north of the Tropic of Cancer. The high rainfall and humidity with moderately high temperature particularly in the wet months, however, tends to make it part of the humid tropics, though from the latitude position this region corresponds to the drier subtropical belts which lie north and south of the humid tropics.

The humid tropics, particularly in South-East Asia, is one of the most densely populated regions of the world. Intensive rice cultivation in the plains and on terraced hill-sides has supported a large population. Much of these lands have of necessity been wrenched from the forest by clearing.

The remaining forest lands are in inaccessible hilly regions or in areas unsuitable for agriculture. There is a constant pressure for clearing of these forest tracts for agriculture. In the hilly region in the south-eastern part of the province, the practice of shifting cultivation has harmful effects on the soil condition.

We shall now consider the major forest types of the region and their effect on the soil and climate. Forest vegetation is often a good index of the interaction of climatic factors. It should, however, be pointed out that, besides the wider zonal climate, there are local microclimatic factors which along with edaphic and biotic factors determine the forest type. The forest community is a complex dependent on all these factors.

The total quantity of rainfall, its distribution pattern, the diurnal and annual temperature variations, the temperature/humidity relationship, the wind speed and the solar radiation received all in turn determine the climate. As pointed out by Champion and Brasnett in their review undertaken for the Food and Agriculture Organization (FAO) (1958*a*), it is clear that there is no general agreement about the classification of world climate. Nevertheless, despite the lack of accurate and consistent classification of the tropical world and of the forest vegetation within it, certain broad classifications of forests on climatic and vegetation criteria exist.

It would seem most appropriate for this exercise to adopt a simple grouping based on Schimper, according to which the forests in the tropics can be classified as:

1. Wet evergreen (rain) forest. Here the dominant trees are mainly evergreen; rainfall is over 80 inches (2,030 mm.) with little or no water deficiency at any period.
2. Moist deciduous forest. The dominant trees are mainly deciduous with a definite leafless aspect in dry seasons; the rainfall is generally 50 to 80 inches (1,270 to 2,030 mm.) or even more in some cases, with a definite dry season of four to six months.
3. Dry deciduous forest. Here the dominant trees are entirely leafless in the dry season; the rainfall is less than 50 inches (1,270 mm.). In the drier areas, this type degenerates into thorn and scrub forests.

Besides the above, there are special types like mangroves in tidal swamps, and the conifers in the border zone representing the subtropics.

In East Pakistan, the major forest tracts are the mangrove formation in the lower Ganges and Brahmaputra delta, and the hill forest of Chittagong. There are also some scattered forests in the central and northern districts.

The mangrove forests of the Sunderbans are not controlled so much by climatic factors as by edaphic factors. These include soil structure, composition, erosion and the mineral constituents of the surface, soil and water. Water movement including changes in water levels also influences edaphic factors. Under the extreme edaphic conditions prevailing in the tidal swamps of the lower delta, the effect of climate is much less, except that the monsoon rain dilutes the salinity of the brackish mud; strong winds may also blow unfixed sand and help to fill up swamps or blow dry salt particles,

and thus influence composition and development. Changes in the soil and water conditions, in any case, have a marked effect on the composition and succession of mangrove forests (Schimper, 1903, p. 839). In the case of recent formations not only is the level of the ground rising due to siltation and wind-blown sand, but they are also getting farther away from the sea as accretion seaward takes place. This affects the salinity of the soil-water complex and consequently the "physiological dryness" of the habitat. Also, the changes in the pattern of tidal flow are reflected in hydrological changes and the nature of siltation at high tides (FAO, 1958*b*). In mangrove tidal forests the soil is stiff mud, a great part of which is clay. It varies from compact blue clay containing little or no organic matter, in the more recent deposits on the sea face and the corresponding river-borne silt on the river banks, to comparatively friable, brownish-black mud containing a very high percentage of vegetable matter in the centre of the islands and towards the mainland. The optimum type is a deep, well-aerated mud, rich in humus but with little or no sand. Where there is regular tidal inundation the subsoil is raw blue clay; in the drier areas there is usually sand beneath the mud.

In the Sunderbans the immense weight of the large quantity of silt brought by the Ganges and Brahmaputra causes gradual submergence of the delta region. Simultaneously the process of siltation occurs. The net effect is the raising of the newer formations while in the older formations the level is maintained to keep pace with the submergence.

The course of succession in the Sunderbans forests starts in different ways. In areas which remain free from inundation at least a few days a month the new mud is colonized by *Sonneratia*. Near the sea face on mud flats the land is inundated daily and *Rhizophora* with stilt roots is the first colonizer. After first colonization the rise in the level is accelerated by wind-blown sand, or by the mud and organic matter held up by the spreading roots and pneumatophores. The course of succession in the next stage depends on factors such as soil composition, salinity and inundation level. In favourable locations where the salinity is not high the climax type is *Heritiera* ("sundri") forest. *Excoecaria agallocha* ("genwā") which is the raw material for the paper industry occurs as a serral forest likely to be replaced in the better type of forests by "sundri". Clear cutting of the forest and replanting of the Sunderbans forest by "genwā" is hazardous as removing the forest cover in areas not subject to daily inundation may bring too much salt to the surface and result in increased physiological dryness.

The Sunderbans forest has to be managed under a system where the existing forest cover is not removed drastically. At the same time the process of ecological succession has to be arrested at the subclimax stage so that the reproduction of the economically important serral stage is ensured. This involves a study of the factors influencing ecological succession such as the salinity of the soil-water complex, the physical structure of the soil and the quantity of solar radiation received by the young trees and the forest floor. While only limited action can be taken to influence the salinity of the soil-water complex by direct inundation, the salinity induced by upward movement of salt as a result of evaporation is a factor which can be controlled by changing the ground tree cover and thereby changing the quantity of solar radiation received.

This factor also has its bearing on the utilization of some of these tidal lands for agricultural purposes, as premature colonization of these lands for agriculture may disturb the delicate salt-water relationship and induce greater upward salt movement, rendering the land unfit for tree growth.

Unlike the mangrove forests of the Sunderbans delta, the hilly forests of Chittagong are better correlated with climatic factors. Over the zone as a whole the rainfall pattern and temperature variations are the main climatic factors; within the zone, however, there are a number of other factors which determine the microclimate and vegetation.

For forest growth and classification, the moisture held in the soil is more important than the precipitation. It is true that in dealing with a complete catchment area all the water entering the basin is in the form of precipitation, but the soil moisture available at a given site depends on the amount of available water retained in the upper layers only where the roots are active. Increasing this available water supply by seepage water, by raising the water table or by decreasing the evapotranspiration may influence the soil moisture required and the forest growth (Pierpoint and Farnar, 1962). These forests accordingly show wide variations within the general type and vary from tropical rain forest to mixed dry dipterocarp forest. In general the forests in the sheltered valleys in the interior approach the tropical rain forest type, whereas on the higher slopes, particularly the western part of the region, they conform to the drier type. From the economic point of view the best forests are in the comparatively dry region where dipterocarp species become gregarious.

Over the greater part of the area, due to high rainfall, the general climatic climax is undoubtedly an evergreen type. Edaphic and microclimatic factors as well as biological factors are often responsible for the development of other subtypes.

The high forests in the Kassalong valley probably represent the true climatic climax of the region in the process of ecological succession. Within the region there are swampy areas with tall grasses and cane-brakes which are fairly stable due to soil and microclimatic conditions such as waterlogging, clayey soil and perennially damp conditions. There is also found a rather open type of forest particularly on the upper slopes, where bamboo predominates with only scattered trees.

These areas are in all probability secondary regression types where the trees may have been cut down and the area burnt. The extensive unclassed forests in the Chittagong hill tracts where the practice of shifting cultivation is allowed also bear a similar type of forest. The few scattered trees in the unclassed forests are definitely of the deciduous type.

The more stable type is a sub-evergreen dipterocarp forest. Though the dipterocarps are never leafless for any length of time—the period to leaf shedding more or less coinciding with the appearance of the new leaf—the forest is definitely less mesophytic than the high rainfall would suggest. The porous nature of the sandy soil and the open nature of the forest floor encouraging evaporation are probably responsible for the creation of this dipterocarp forest. In some of the hills where the strike of rock slopes steeply to the east, the western aspect drains so completely that a decidedly dry deciduous type of forest is developed. Conditions in the typical dipterocarp forests are not so dry but even here the evergreen character of the forests is often absent. The dipterocarp groves near villages are probably the result of annual fire and grazing. Despite intense maltreatment the dipterocarp survives when all else is eliminated (Ghani, 1957).

In addition to the microclimatic, edaphic and biological factors stated above, the management pattern of the forest itself is affecting the ecological status of the forest.

The general pattern of working these hilly forests is to clear fell the existing low-value heterogeneous forest and then to plant it with teak and other deciduous species. Though teak is an exotic in this area, it has been planted successfully for about 100 years. Pure plantation of teak in association with *Lagerstroemia* creates a deciduous forest and as such definitely changes the ecological status of the forest. Economically it is undoubtedly profitable to convert the low value heterogeneous forests to high value homogeneous forests of teak and a few associate species. It is, however, necessary to study the implication of this drastic method of changing the composition of the forest. While, from the utilization point of view, conversion of this forest to a pure teak forest is highly desirable, the forest service—as guardian of national forests—is always vigilant so that the immense benefits conferred by forest vegetation on the soil in the watershed areas are not belittled when planning the economic exploitation of these forests.

There has been some apprehension that pure teak plantations are likely to deteriorate the soil. Research in southern India has shown that second rotation teak plantation has not resulted in any soil deterioration. It might be argued that Chittagong is outside the habitat of natural teak and the loose soil here is more liable to erosion. Though preliminary indications are that soil erosion under teak plantation is not a severe problem, further research probably is necessary. Along with the question of erosion the risk of laterization is also to be considered. In the tropics where alternate dry and moist seasons prevail there is a strong tendency for laterization of the soil. If during dry periods there is an upward movement of water, the various products of the weathered rock such as silicic acid, sesquioxides of aluminium and iron, and aluminosilicates in solution will travel to the surface. After oxidation at the surface and in basic pH, the sesquioxide will become insoluble, but the other soluble minerals will be washed away by rain. There will thus be an accumulation of the oxides of aluminium and iron at the surface. Dearth of humus by increasing the pH value and by hastening of oxidation helps this process known as laterization.

Where the water movement is largely downward so that the leaching is continuous and where the pH is acidic due to accumulation of humus, the opposite process of podsolization takes place.

The soil under the evergreen forest in Chittagong is a yellowish loam superimposed on the red subsoil. The yellow colour results from the leaching action of humus on the original underlying red soil. Vageler regards it as a sort of podsolization, being the result of evergreen forest cover which induces less erosion and less evaporation. Mohr, in Java, found that precipitation of less than 3.2 inches in the dry month leads to upward movement of water in the soil. In Chittagong the dry months are from November to February when rainfall is less than 2 inches per month. The rainfall during the hottest months of April and May is 4.12 and 10.86 inches respectively. Taking the analogy of Java, the only month when there is the chance of significant upward movement of water is March when the rainfall is 2.46 inches and the temperature appreciably high. Even then the chance of such upward movement would be negligible under forest cover where the temperature would be lower and humidity higher (Ghani, 1957, p. 33).

Chemical analysis of the constituents of the different soil profiles reveals the dual nature of the soil. The low pH value, the accumulation of sesquioxide and decrease of SiO_2 in the B horizon points to podsolic nature, whereas the high sesquioxide content of the A horizon and the low SiO_2/Al_2O_3 ratio of the HCl extract points to lateritic nature. Here we find two opposing processes struggling. The lateritic tendency has been suppressed in favour of podsols under evergreen forest cover. Such mixed soils are often found in border-line conditions. According to Vageler, in regions of yellow and brown soil and in the soil under primeval forests in tropics and subtropics, the podsolic acid hydrolysis overtakes the primary lateritic weathering which characterizes such soils when they emerge with only a scanty cover of grass. With evergreen forest formation, greater coolness, humidity and lower pH due to humus accumulation result in podsolization and soil degradation by laterization. Where erosion is not a factor

and evergreen undergrowth can be induced to come up under teak plantation, the danger of laterization is not great (Ghani, 1957, p. 33-34).

The delicate balance between podsolization and laterization can, however, be tipped if soil erosion sets in. The result of erosion would be truncation of soil profile to the B horizon for it will then be the top horizon. Being low in SiO_2 and high in Al_2O_3 and Fe_2O_3, this will behave as a lateritic one. The ferruginous crust will reduce vegetation and humus accumulation, and further laterization will go on.

Though from the utilization point of view, it may be desirable that the heterogeneous forests should be clear felled and restocked with pure plantations of valuable species, caution will have to be exercised when fundamentally altering the ecological formation.

The purpose of this paper is to highlight some of the problems of management of the forest land in the humid tropics. It should be reiterated that in the humid tropics the forests are often in the regions unfit for agriculture. Colonization of these marginal lands for agriculture may cause harm by exposing the soil cover frequently. Forest management and colonization of marginal land should be practised with caution so that irreparable damage is not done to the land, one of our most precious heritages.

Résumé

L'influence des forêts sur le sol et le microclimat dans la zone tropicale humide (Q. Ghani)

L'auteur traite de l'influence des forêts sur le sol et le microclimat dans la zone tropicale humide, en ce qui concerne plus particulièrement les forêts du Pakistan-Oriental. Il étudie la répartition d'ensemble et les caractéristiques générales de la flore forestière du Pakistan-Oriental, en insistant spécialement sur les forêts à mangrove de Sundarbans, dans le delta du Gange, et les forêts de dipterocarpes des zones montagneuses. Dans le cas de Sundarbans, la formation, la composition floristique et la succession obéissent principalement à des facteurs édaphiques, qui comprennent la structure et la composition du sol, l'érosion, la teneur en minéraux, la période d'inondation et la circulation périodique de l'eau. Les forêts des régions montagneuses, au contraire, sont dans une grande mesure influencées par des facteurs climatiques. Le type forestier dépend de la quantité d'humidité retenue dans le sol. De grandes variations du type général de végétation s'expliquent par des degrés différents d'humidité dans le sol. La formation forestière ombrophile type ne s'observe qu'à l'intérieur des vallées abritées, alors que, sur les pentes supérieures et sur les versants occidentaux exposés, dominent les forêts sèches mélangées de dipterocarpes.

L'auteur a examiné les répercussions de la sylviculture sur le microclimat et le sol. Alors que dans les forêts à mangrove les pratiques sylvicoles actuelles ne modifient pas profondément les conditions écologiques, l'aménagement des forêts de montagne tend à modifier les conditions écologiques de la forêt sempervirente hétérogène et à la faire évoluer vers une forme moins mésophytique. L'auteur examine les conséquences de cette évolution et il souligne la nécessité de poursuivre les recherches.

Discussion

K. Pranich. With reference to this paper and the previous one may I make a few remarks. In the lower part of the delta where the water is brackish in general there are losses of waste land or land where not too valuable vegetation is grown. I know that FAO has made many studies on salt tolerance of paddies, but I have not yet heard of other studies regarding other grain crops or tree crops. It would be most valuable if Unesco in co-operation with FAO could conduct research on salt tolerance of other crops such as coconuts, bananas, papayas, mangoes, etc. If it should prove by such research that some fruit crops or other grain crops have also high salt tolerance, it would be of great economic value to put these waste lands into good use.

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IV

Biology

Biologie

Problems presented by soil microbiology in the humid tropics with reference to the deltas

B. N. Singh

Microbiology includes the study of viruses, bacteria, fungi and actinomyces, algae and protozoa. Although these microbes are perhaps the oldest inhabitants of this world, the entire history of soil microbiology covers no more than a period of eighty to eighty-five years. Soil microbiology arose in an attempt to account for certain chemical processes, such as oxidation of ammonia and fixation of nitrogen, already shown by chemists to take place in soil. Thus, unlike the developmental history of botany and zoology, soil microbiology has had a highly atypical development. Morphology, taxonomy and ecology of soil micro-organisms, harbouring different types of soils, have not been properly studied. In the humid tropics the study of soil microbiology has been so far neglected and the present state is such that none of its aspects or divisions is free from the urgent need of basic research.

The interdependence of soil micro-organisms and physico-chemical conditions of the soil must be fully appreciated if any progress is to be made in understanding the problems relating to soil fertility. The size and the quality of the microbial population is determined and limited by environmental factors such as the quality and availability of food materials, pH, moisture, aeration, temperature, etc. The soil environment is one of the most dynamic sites of biological interaction in nature.

It is well known that a fertile field soil in the temperate zone contains teeming millions of a complex population of microscopic life consisting of bacteria, fungi, actinomyces, algae, protozoa and so on. The populations are not only large but also very varied. They are of great importance to crops since some of them are the agents that prepare the soluble food materials available to crops. Different types of organisms differ very much in this respect so that not only the quantity but also the quality of the microbial population must have an important influence on crop growth. Before we try to answer the question generally asked by a layman—How can the study of soil microbiology produce results of practical importance to agriculture?—it is important to answer the primary questions: (a) What are the common species of micro-organisms present in different types of soils? and (b) Why are they common? Answers to these questions may provide means for encouraging the predominance of the more useful species and the suppression of the harmful types, and so improve the soil's fertility.

The effects that micro-organisms and their metabolic products have on one another are very varied and complex; it is moreover becoming increasingly evident that they are of great practical interest to mankind; this is true in many industrial processes, in the soil, in animal tissues, and hence in the treatment of disease. The interaction may be due to straight-forward competition between organisms with the same needs occupying the same habitat, or to the effect that the metabolic product of one may have upon the existence of the other or to the fact that one group of organisms preys upon the other. The dominance of certain groups and the prevalence of organisms having specific effects, whether beneficial or harmful, will determine what role they will play in a particular soil. Any attempt to produce the beneficial changes in the soil population, by the encouragement of organisms producing desirable biochemical activity or by the suppression of the pathogens, must take into consideration the complex interaction between different groups of micro-organisms.

Russell and Hutchinson in 1909 showed that the increased fertility of partially sterilized soil by volatile antiseptics was due to a great increase in microbiological activity. They suggested that it was brought about due to the changed equilibrium between the components of the micropopulation. The more recent work at Rothamsted on "partial sterilization" by steam and formalin, under field conditions, has shown that the qualitative and quantitative changes brought about by these treatments in the microbial population persisted for more than a year. Therefore, the dominance and persistence of micropopulation brought about by

external factor or factors will greatly affect soil fertility.

According to Russian microbiologists, it is possible to increase soil fertility of certain Russian soils by the application of preparations of azotobacterin and phosphobacterin. The successful establishment of organisms introduced in field soil is by no means easy because of the existence of antagonistic micro-organisms. However, the work of Russian workers does suggest that the subject of bacterial fertilizers should not be neglected. The value of *Rhizobium* in nitrogen fixation is widely recognized and is less controversial. Study of polysaccharides and related compounds, produced by micro-organisms, has an important bearing on soil crumb structure and humus formation in soil. Microbiology of rhizosphere and mycorrhiza has an obvious practical importance on the growth of crops and the prevention of certain root diseases caused by biological agents. The effect of pesticides, herbicides, insecticides, fungicides and nematocides, on non-pathogenic microflora and microfauna must be carefully determined, otherwise some important group or groups of micro-organisms needed for nutrient transformations might be eliminated and the crop yield reduced.

In discussing the subject of soil microbiology in the humid tropics, it is difficult to know where to begin. One could pick out many basic problems needing study, each of which should lead to knowledge that would have ultimate importance to agriculture. It is well known that in hot tropics organic matter, added to soil in order to maintain the tilth and the water-holding capacity of soil, quickly disappears because of oxidation due to micro-organisms and thus leads to soil erosion. Joint efforts of microbiologists, organic and physical chemists are needed to discover ways and means to prevent this rapid break-down of the organic matter in the tropical soils. The demand for nitrogen is bound to increase owing to the rising world population. The resources of industrial power to produce artificial nitrogenous fertilizers are not inexhaustible in the long run. Leaching and denitrification are bound to aggravate the situation. Therefore, the possibility of supplying nitrogen to the soil by biological nitrogen fixation must be thoroughly explored.

When a soil is waterlogged, as happens in rice-fields, there is a decrease in the abundance of aerobic micro-organisms and a parallel stimulation of the anaerobes. This change is due to the disappearance of free oxygen as a result of its utilization by oxygen-requiring micro-organisms. There is a shift from aerobic to anaerobic transformations. A detailed study of the microbiology of waterlogged soils has yet to be undertaken. In this connexion, it may be of interest to recall the theory of "partial sterilization" of Russell and Hutchinson. According to this theory, "soil sickness" is due to an excessive number of active (trophic) protozoa which by their phagocytic action restrict bacterial processes going on in the soil and the remedial effect of "partial sterilization" by killing these protozoa by sterilizing agents. Although it has been shown by Singh and Crump, at Rothamsted, that the beneficial effect of "partial sterilization" under field conditions is not due to the killing of amoebae, numerically the most important group of soil protozoa that feed selectively on bacteria, it would be of interest to study the role of protozoa in waterlogged soils. Due to waterlogging, ciliates and other protozoa, which do not lead an active life in field soil due to the lack of sufficient moisture, may become abundant and interfere with the transformations carried out by bacteria. It has been suggested that in paddy-fields the increase in nitrogen is due to algal growth. The algae, by photosynthetic process, also liberate molecular oxygen and thus provide part of the oxygen requirement of the submerged roots.

In delta regions, where large quantities of alluvial soils are transported, it is important in their reclamation to determine the factors that will lead to the establishment of useful micro-organisms needed to build up the fertility of these soils.

The main lines along which work is most needed in the humid tropics are as follows:

1. A survey should be made of the distribution and numbers of the main groups of micro-organisms in different types of soils, using the counting methods recently evolved and also by discovering new ones.
2. A survey should be made of the soil bacteria, actinomyces and fungi, classified in accordance with their nutritional requirements and related to soils of known type and manurial treatment.
3. The conditions that make the predominance of a group of organisms in the soil necessarily in competition with other groups needs to be studied both in the field and in the laboratory.
4. The behaviour of soil organisms towards mineral constituents of soil and particularly towards phosphates and iron compounds needs study.
5. The production of polysaccharides and particularly of amino-sugars by micro-organisms needs investigation. This question probably underlies that of soil crumb structure and also of humus formation.
6. The decomposition of polysaccharides, especially cellulose, is still not understood. But both this subject and that mentioned in No. 5 must be investigated in close co-operation with biochemists.
7. The relation of soil organisms to plant roots (the rhizosphere, the problem of mycorrhiza and the possible antagonism from soil organisms against root disease fungi) requires study.
8. The nodule bacteria offer a whole range of fundamental problems: How, why and when do they produce mutant types? How are they affected by plant root secretions? What prevents them infecting the "wrong" host plant? How do they stimulate cell multiplication to form the nodule? Do they induce polyploidy in the nodule cells, and if so, how? What makes a given strain effective or in-

effective in a given host plant? How do they fix nitrogen? Why do they eventually become parasitic and attack their own nodules? etc.

9. It would be of great interest to find out what nitrogen-fixing micro-organisms among the free-living non-symbiotic groups are common in different types of soil and to encourage their growth in their natural habitat.

The available techniques of increased crop production are nearly exhausted and the future can hold promise through basic research. An integral and important part in any plan of increased crop production in the humid tropics will be an elaborate scheme for long term intensive study in soil microbiology. I suggest that a proper beginning be made by creating centres for tropical soil microbiology research consisting of specialists in different branches of soil microbiology and allied sciences. This will help in contributing to an integrated picture of soil science and soil conservation. The knowledge so gained may be utilized for practical agriculture in the humid tropics. These centres may also provide facilities for the training of personnel.

Résumé

Les problèmes de la microbiologie des sols dans les régions tropicales humides et en particulier dans les deltas (B. N. Singh)

A l'origine, la microbiologie des sols a pour objet d'expliquer certains processus chimiques tels que l'oxydation de l'ammoniaque et la fixation de l'azote, dont les chimistes avaient déjà démontré l'existence dans le sol. On n'a donc pas suffisamment étudié la morphologie, la taxonomie et l'écologie des micro-organismes édaphiques au sens large. Le sol est l'un des milieux naturels où l'interaction biologique est la plus forte, et une bonne connaissance de l'interdépendance des micro-organismes édaphiques et de l'état physico-chimique du sol est indispensable si l'on veut arriver à comprendre les problèmes relatifs à la fertilité du sol.

Les travaux effectués à la station expérimentale de Rothamsted sur la « stérilisation partielle » par la vapeur et le formol, en milieu naturel, ont montré que les modifications qualitatives et quantitatives dues à ces traitements de la population microbienne durent une année au moins. La prédominance et la persistance de micro-organismes dus à des facteurs extérieurs influeront donc fortement sur la fertilité du sol. Il importe de déterminer : *a*) quelles sont les espèces de microbes communes à divers types de sols; *b*) pourquoi elles sont communes à ces sols. On pourra ainsi contribuer à la prédominance des espèces les plus utiles.

Dans les régions tropicales humides, l'étude de la microbiologie du sol a été négligée, et l'état actuel des connaissances est tel qu'il y a lieu de faire des recherches fondamentales sur tous ses aspects et toutes ses subdivisions. Dans les régions deltaïques, où est transportée une forte quantité de sols alluviaux, il importe, pour pouvoir récupérer ces sols, de déterminer les facteurs qui favoriseront l'établissement de micro-organismes utiles, nécessaires à leur fertilisation.

Les techniques qui permettent actuellement d'accroître la production agricole ont presque toutes été exploitées à fond et l'on ne peut espérer en l'avenir que si l'on fait des recherches fondamentales. Il conviendrait sans doute, pour commencer, de créer des centres de recherches sur la microbiologie des sols tropicaux, qui contribueront à relier intimement l'étude de la conservation du sol à la science du sol. Ils pourront également former du personnel.

The biology of fresh, brackish and saline water as it contributes to tropical delta formation[1]

M. S. Doty and D. Mueller-Dombois

Considerable attention has been given to both the biological and physical factors that lead to the formation of the vast and highly productive tropical delta regions, such as those which produce much of the food utilized by the people of South-East Asia. The physical factor of reduced turbulence where rivers meet the sea and where the waves and ocean currents are broken on the shore has been accorded a great role in delta formation. Less has been said about initial deposition of sediments in the sea and their redeposition on the shores by the landward transport of these sediments brought about by waves and tidal action. Flocculation of fluvial sediments in the brackish-water zone of a temperate stream led one of us to the conclusion that factors other than reduced turbulence seemed responsible for some types of sedimentation, in this case the precipitation (as salting-out) of river-borne organic colloids when they reached the electrolyte sea-water. This idea led us, still further, to consider the interaction of organic with inorganic components in the brackish water (poikilohaline) region and in the construction there of deltaic land.

Classical deltas protruding into the sea, as in the case of the delta of the Saigon and Mekong rivers, or deltas occupying sunken river beds or filling bays, as in the case of much of the great plain of Thailand, may occur even where there is an absence of one or both of the sources of turbulence—sea and river. The changes in deltas as they begin to form, grow, mature and enter into a new cycle have been described in predominantly physical terms. Initially, at least, the process of the dumping of a river's load of erosional material at the seaward end of the stream and the forming of the subaquatic base of the delta is largely geological. "Foreset" is the geologist's term for this base. However, on the upper surface of the foreset the horizontal "topset" bedding and the subaerial land of a delta arise not only through deposition of inorganic matter as a result of physical factors such as mentioned above but also as a result of biological activities of one sort or another. The material comprising foreset beds contains usually less than 0.2 per cent organic matter, whereas the material of topset beds contains often 2.0 per cent or more organic matter.

Our task here is to outline some of the bio-ecological factors and problems concerned with this organic matter and the biological activities relating to the interaction of aquatic and terrestrial phases in tropical delta formation.

Delta-like land formation also occurs where there is no great inland area or constant supply of delta alluvium by streams. In many such cases in the Philippines and in Hawaii delta-like deposits seem to be advancing over reef flats. Reef flats in themselves are biological in origin, largely the result of purely algal activity or of symbiotic relationships between algae and coelenterates. While their seaward edges may be above low-tide level, inshore reef surfaces are lower, perhaps through solution of the carbonate material in relation to oxidation of organic matter, as happens in tropical delta soils. Probably many such delta-like plains receive their deposits as sheet-wash erosional material or as erosional material arriving with the run-off from occasional storms. They are protected from the erosional forces of the waves striking the open coastline and persist largely as a result of biological stabilization. Our point here is that without such a base of biological origin the small amount of sedimentation provided from shore and sea would probably not result in delta-like land formation.

A comment here on the movement of water and material over subaerial deposits seems pertinent. Along channels through mature delta regions, the water and mud move from deep water out over the topset during periods of flood tide and river freshet. Examples

1. The authors were assisted by financial support from the Office of Naval Research through Contract No. Nonr-4108(00) and from the Graduate Research Funds of the University of Hawaii.

of this situation are found in the Saigon river region and Pandan Natural History Preserve in Singapore where trees are rooted at the edge of the deep water beyond the foreset. In cases of incipient deltas and delta-like land formations in bays and on old reef flats, such as can be seen in the coves of Catanduanes Island and at Puerto Galera in the Philippines, the mud is brought by the fresher water from the shore out over the topset into the deep water of the channels. In this latter situation there is almost always a significant area between the deep water of the channels and the forested habitats that is predominantly populated with algae—often the sediment producer *Halimeda*—as though the algae were pioneers preceding the mangroves.

In Hawaii our attention has been drawn to delta formation, for there is a shortage of agricultural land and shoreline land for commercial and recreational development. In Hawaii natural delta-like land formations occur mostly as mud flats or as very young mangrove swamps. There are artificial delta-like land formations as a result of rock fills, debris and earth dumped on sea-reef flats. The famous fish-ponds of Hawaii are becoming filled by sedimentation and converted to other uses. Hawaiian delta-like habitats are unique biologically in that mangroves, which do not occur natively this far to the north-east in the Indo-Pacific Biogeographic Province, have been but recently introduced. *Rhizophora mangle* was introduced in 1902. Other species were introduced in 1922. Mangroves are now spreading and in some places *R. mangle* now occurs far out from shore on reef flats as a small, shrub-like tree. At these sites salinities lower than 34 per mille seem not to occur and in the holes in the reef flat where they have taken root there sometimes seems to be no sediment. An understanding of the biological factors that may control the extent and future nature of these delta-like land forms, whether artificial or natural, seems of utmost practical value. With mangroves now spreading rapidly on all tidal mud flats, as they do characteristically in the tropics, it would seem that this particular biological force is to become one of major importance in Hawaii.

Generally overlooked in the formation of tropical deltas is the probable function of dissolved organic matter. This can be described as follows. As much as 20 grammes of dissolved organic matter per cubic metre has been reported in inshore marine water. This amount is probably exceeded by the amounts in brackish waters. As much as 50 per cent of the photosynthate produced by sub-aquatic delta vegetation may be lost from the botanical population by becoming dissolved in the water. Recently it has been shown that this dissolved organic matter can be converted directly to organic particles. Much of this dissolved matter must be adsorbed on to river-borne inorganic particles during the electrolytic flocculation process. More than one study has shown that the floatability of the particles which come to compose delta lands is reduced when the adsorbed organic component is removed artifically.

When the river water carrying particles to the sea is mixed with the even more dense sea-water, the resulting brackish waters buoy the particles even more strongly. The smaller more buoyant particles, having a much greater surface to volume ratio and thus carrying a relatively greater load of adsorbed organic matter, will be carried farther. Thus they are flooded out over the topset beds of the forming delta and deposited there especially during flooding tides and freshet periods, or carried farther at other periods and contribute even to the bottomset offshore beyond the foreset, rather than becoming deposited on the foreset area.

In tropical deltas organic matter appears from a number of other sources. The appearance of dissolved organic matter from photosynthate and its role has already been discussed. The death of the freshwater and marine stenohaline organisms, when moved into the brackish water habitat, must contribute a large amount of the organic matter found in young delta alluvium. The sedentary algae, animals and plants that are killed by being covered with sediments during topset formation are another significant source of organic matter. They produce inorganic matter, largely as the fine remains of marine planktonic or benthic algae or coarser animal skeletal fragments.

The tropical delta organisms are relatively few in number of taxa but vast in number of individuals. Those that are long-lived are for the most part motile or grow predominantly upwards. In their habitats they often appear in "pure" stands of great density. As examples, in some places *Nipa* palm and mangrove forests can hardly be penetrated by a man. The *Salicornia* flats of the temperate regions and the *Batis* flats of the tropics are well known for their monotony, that is, for the small number of species and the high density of these few species.

It is pertinent here to speak in reference to the phytocoenological status of Hawaii's more advanced or older delta-like land forms. They are in coves which themselves are usually in embayments often sheltered, in turn, from wave action by a barrier reef. The soils here are perhaps not characteristic of delta-alluvial soils. However, trees may cover them that are over 10 metres tall, but are perhaps only 30 years of age, and we must consider the soils as very young. On the other hand, solonchak soils are reported in Hawaii and it is of pertinent interest to develop an understanding of their possible origin before the introduction of mangroves. There are other sea-shore plants which might possibly have played an as yet unassessed role in the formation of such soils in the past in Hawaii when the more universally known delta and mud-flat plants were absent.

We also must express concern for developing an understanding of the biological means of stabilizing

deltas in their most productive stages. This stage we accept, anthropocentrically, as being achieved when the greatest area of subaerial land has matured and may have formed soils of solonchak-like properties.

So far in the Hawaiian islands and elsewhere as well, we have been impressed with the idea that studies of deltas have been narrowly couched or have not gone far enough. They seem to have been either strictly biological and even more narrow than that, usually strictly botanical with emphasis on mangrove populations, strictly soil studies or strictly geological. There seems to have been little combination of all types of information, that is there has been little of the integrated or ecosystem approach to formulating explanations of the functional relationships between the plants, other biotic elements and the environment under these special conditions.

One might describe the usual studies that have been made of tropical deltas as the stock-taking steps anyone should take when they come on to a new job. They are invaluable steps. In the case of deltas these steps are concerned with area and depth distributional studies of the biological and physical elements. The completion of the studies of all factors in respect to their distribution along profiles extending from the fresh-water source of inorganic materials to the open sea along salinity gradients is to be encouraged.

Rate studies are next and should be considered the terminal stages in the stock-taking process. These can be grouped into two categories: (a) studies of integrated chronosequences of both the biotic and environmental components; (b) studies of the equilibrium relationships between rates of energy and matter, i.e., productivity studies.

Tropical deltas are acknowledgedly among the most productive areas in the world. That is to say, the rates at which inorganic matter and energy are converted to organic matter per unit area and per unit time are generally greater than they are for the seaward or landward adjacent areas. The purpose of this paper is not to discuss the causes of this great fertility but, recognizing the resulting value of tropical deltas, our purpose is to point out biological facets in their formation and stabilization. We have selected some facets we feel to have been considered and studied far too little up to the present. The following among them are largely related to aquatic biology:

1. The special biological environment of brackish water habitats or delta regions and delta-like land forms which are densely populated by a few geographically widespread generic taxa.
2. The probable role of dissolved organic matter in the brackish water zone.
3. The role of brackish water in respect to flocculation.
4. The effect of mortality of marine and freshwater populations in the brackish water zone.
5. The effect of periodic or continuous sedimentation on the biological populations established on topsets.
6. The presence of reefs as a quasi-foreset for tropical delta-like land formation.
7. The role of organic matter in relation to the removal of carbonate from delta soils.
8. The formation of delta-like habitats in tropical regions where there is little in the way of an extensive or continuous land contribution.

Résumé

La biologie des eaux douces, saumâtres et salines considérée dans ses rapports avec la formation des deltas tropicaux (M. S. Doty et D. Mueller-Dombois)

Les deltas tropicaux figurent sans contredit parmi les régions du monde les plus productives. Cela veut dire que les vitesses auxquelles la matière minérale et l'énergie se transforment en matière organique par unité de surface et par unité de temps y sont généralement plus grandes que dans les régions terrestres et maritimes voisines. Nous nous proposons non d'étudier les causes de cette grande fertilité, mais, reconnaissant la valeur qu'elle donne aux deltas tropicaux et aux formations de terrain du type delta, de mettre en lumière les aspects biologiques de leur formation et de leur stabilisation. Nous avons choisi quelques-uns de ces aspects qui, à notre avis, ont été jusqu'ici bien peu examinés et étudiés. Ceux notamment qui sont énumérés ci-après intéressent dans une large mesure la biologie aquatique :

1. Le milieu biologique particulier des eaux saumâtres ou des deltas et régions deltaïques très peuplées par quelques taxa génériques à large diffusion géographique;
2. Le rôle probable de la matière organique dissoute dans la région d'eaux saumâtres;
3. Le rôle des eaux saumâtres en ce qui concerne la floculation;
4. L'effet de la mortalité des populations des eaux marines et des eaux douces dans les régions d'eaux saumâtres;
5. Le rôle de la sédimentation périodique ou continue de la couche supérieure en ce qui concerne les populations biologiques;

6. La formation des récifs comme couche quasi frontale dans la formation des deltas tropicaux;
7. Le rôle de la matière organique du point de vue de l'élimination du carbonate des sols deltaïques;
8. La formation d'habitats deltaïques dans les régions tropicales où les apports terrestres sont peu importants ou discontinus.

Les études de delta qui ont été faites jusqu'ici dans les îles Hawaii ou ailleurs ont été conçues de manière trop étroite ou n'ont pas été suffisamment poussées. Certains des aspects biologiques de la formation des deltas tropicaux dont il a été question ci-dessus ont été rarement examinés de façon approfondie. Il semble que l'on n'a guère associé tous les types d'information, c'est-à-dire que l'on a peu utilisé la méthode intégrée ou méthode de l'écosystème pour avancer des explications des rapports fonctionnels existant entre les végétaux, d'autres éléments biotiques et le milieu dans ces conditions particulières. Les études qui ont été faites sont essentiellement des inventaires destinés à déterminer les facteurs qui interviennent dans une région deltaïque. Il convient d'encourager l'achèvement des études de tous les facteurs et de leur variation en fonction de la répartition le long de profils s'étendant de l'origine en eau douce des matériaux jusqu'à la mer libre suivant les gradients de salinité. Puis viennent les études de taux, qui devraient être considérées comme les étapes finales de ce travail d'inventaire. Ces études de taux peuvent être groupées en études des chronoséquences intégrées des composantes biotiques et mésologiques et en études de la productivité des différents résultats finals.

Discussion

F. R. Fosberg. I would like to draw attention to the relationships between these delta ecosystems and surrounding ones to possible dependencies between productivity in the delta and economic resources in the surrounding seas, and to the importance of understanding these before we alter delta conditions too drastically. We have the example of our temperate salt marshes, which have for a long time been regarded as waste land to be drained or filled in. Now that we have practically destroyed them we find that great populations of marine fish and crustacea, regarded as important food resources, are dependent in their younger stages on the shelter and organic production of the salt marshes. We may well suggest that in the tropical deltas thorough biological studies be made, in order to understand these ecosystems before we let the engineers drain them completely and surround them with embankments, thus losing permanently whatever resources have their bases here.

D. Mueller-Dombois. I would like to follow up on Dr. Fosberg's comments and also to refer to an important paragraph of my paper. I want to stress the need for co-operation between scientists in deltaic studies. Far too much work has been done by botanists, geologists, zoologists and hydrologists working independently of each other. The problems cannot be tackled in this way and this symposium has been designed particularly to bring us all together. It is not sufficient to come together just occasionally. From the very outset we need to attack the problems together or else there is a great danger that what Dr. Fosberg has described might occur—indeed I know from my own experience how the New England marshes have been intersected by mosquito ditches which have altered the original conditions and made the marshes less valuable as biological entities. I would hope that as a result of this symposium the same mistake will not be made in the deltaic regions of the humid tropics. If concerted attacks are made I would endorse the plea of Dr. Fosberg that we learn something about the natural environment before proceeding with wholesale hydrological and engineering works.

H. Boesch. I would like to make an additional remark. I assume you mean dry matter in productivity.

I would also call attention to the fact ICSU through IUBS is working on the international project of IBP. ICSU has decided to go ahead in measuring productivity in natural and cultural habitats.

D. Mueller-Dombois. We must certainly be primarily concerned with the physiological potential before going ahead with the study of the products. I have been in contact with IBP.

F. R. Fosberg. We should not lose sight of the relationship between delta ecosystems and the surrounding ecosystems. Fish life is often dependent in the young stages on salt marshes. In eastern United States many salt marshes were destroyed and it has not been found that fish and crustacea were dependent on those salt marshes. We should have intensive biological studies before engineers drain and alter areas.

D. Mueller-Dombois. I would like to briefly elaborate what is meant by "ecosystem" (*sensu* Tansley, 1920). It consists of the biotic and physical components occurring in the same locality that interact by influencing one another and thereby act as a whole system. In a typical forested ecosystem, for example, the biotic component consists of trees, shrubs, herbs, mosses, lichens, animals and micro-organisms; the physical component consists of the place itself, of climate, soil (with its various horizons), substratum, soil water and nutrient systems, among other things. Scientific teamwork seems most useful if people representing different disciplines or viewpoints study the same object. The ecosystem concept leads to such an approach in the field as it accommodates the study objects of different disciplines into an orderly systematic relationship. The ecosystem thereby becomes the ultimate, common object of the different viewpoints of study. It is significant that the people in this symposium represent by their special fields several major parts of the delta ecosystem; thus, one aspect of the concept is already put into practice by the organizers of this symposium.

Biology of estuaries

H. Caspers

There is a strong division in the type of river outflow to the sea. Our primary concern in the discussions of this symposium is the deltas. But we need to look also at the second type, i.e., the estuaries, to compare the geographical and biological conditions in both. Only in this way will we learn how to explain the characteristics in each type. And in the end, I think, this comparison will show that the differences are not as great as they seem to be according to the classical definitions.

It is a basic idea of science to combine the individual facts of one biotop with those of others to find the common feature. But there is the danger that we may forget that in nature the reality is individuality. Mainly in the study of river mouths we see how decisively the local geographical, hydrographical and climatical conditions stamp the biological feature.

As one can see from the literature, until now the specialities of river mouths have not yet been studied sufficiently to enable us to offer definitive results with regard to a clear system of types as basis for typification. But some work has already been done and this enables us to present a preliminary system. Classical studies have been carried out in England, and also from the Elbe estuary—my present object of study—we have biological reports from as far as the beginning of our century, which permit comparison with present conditions. For such a comparison the questions of pollution must be taken into consideration. In all industrial countries river mouths are a main region of development, of harbour centres, power stations, domestic sewage, etc., all of which influence the present biological situation.

A great number of different types of tropical estuaries have been studied by Professor Day and his school in South Africa, and there are publications on estuaries in Australia by Rochford and others. Unfortunately the biology of the largest estuaries remains quite unknown: that of the Amazon and the Chinese rivers.

At the present time the estuary of the Elbe seems to be the best studied river mouth of this type, but on the whole we have to emphasize what Pritchard wrote in 1950: "In the case of estuaries we are yet some fifty years behind the studies in the open ocean."

A main feature of the estuaries is the poikilohalinity, therefore the most important characteristic of an estuarine population is its ability to tolerate changes in salinity. The main currents in an estuary are due to the inflow from the river and the rise and fall of the tides. This develops a high degree of variation. In horizontal extension we have a spectrum of salinity degrees from a polyhaline to different steps of mesohaline regions. It may be astonishing, but it is a characteristic of the clean type of estuaries that we have estuarine conditions even in regions of the river mouth beyond which the tidal current does not transport salt water. As we have seen, the tides form special conditions in the estuary, and this includes the development of tidal flats on the muddy borders of the river. The pressure of the flood prevents the outflow of the river with the consequence that the water level rises; in contrast, at ebb-tide the outflow is quicker, thus tidal flats develop also in the freshwater area of the river mouth. As this influence of the tides is characteristic of the estuary it is possible to fix the upper limit of the estuarine region by the end of a tidal change of the water level.

Let me describe the conditions in the Elbe river as such a type of estuary.

The polyhaline, α- and β-mesohaline and oligohaline zones cover only about half of the estuarine part of the river which still shows a tide-influenced zone more than 70 miles beyond the end of sea-water influence. In the middle part of the mesohaline area can be distinguished a "zone of death" where on the one hand the freshwater plankton floating down the river enter into water too highly saline and die, on the other hand the marine plankton pressed into the river mouth reach the limit of their salinity tolerance and also die. This can be seen from ships in the form of a

cloudy, muddy water filled with detritus. The Secchi disc is only to be seen 5 cm. deep!

As regards the conditions of the bottom community, in the polyhaline zone a well-developed marine biocenosis still exists but the echinoderms soon reach the end of their salinity tolerance. In the mesohaline zones we have a restricted marine fauna. This is combined with a change in the bottom structure: in the exposed front of the river mouth there is a fine detritus transported down by the river and deposited in the open sea. In the narrower parts the river bed is covered by fine sand; all detritus is washed out. Here mainly an endobiosis of marine polychets and amphipods finds suitable conditions for living. But in some areas the bottom is covered by *Mytilus:* this mussel of marine origin owing to its byssus threads, resists the strong current. In the spaces between mussel populations a lot of amphipods—mainly *Gammarus*—find an ecological niche. But which bottom community do we find in the freshwater part of the estuary? Here the answer is easy: in the sand and gravel of the river bed no animal of the macrofauna finds conditions adequate for life. This is astonishing when compared to bottoms of the same structure in the mesohaline area of the estuary showing a reduced but nevertheless rich amount of marine animals. The explanation, I believe, is that in fresh water there do not exist ecological types of animals which are able to resist such conditions. It is different in muddy areas, for instance in artificial harbours (Hamburg), covered by a thick layer of detritus from domestic sewage where we have a community of oligochets (Tubificidae), with 800,000 worms per square metre in some parts.

The above description concerns the macrofauna. In the microfauna we find different conditions. Here there is penetration of the whole estuary by marine animals, such as nematods and turbellarions, which cross through the different stages of salinity decrease and also enter into the freshwater regions. Many of them live in the interstitial spaces between the sand grains. We are just beginning an intensive study of this fauna.

In the tidal flats of the river borders we also find changes in the marine communities with the decrease of salinity. In the freshwater flats there is a rich endobiosis of tubificids and larvae of chironomids. This is the same community that we find in the hypolimnion of eutrophic lakes, and these ecological types are able to survive the hard conditions of the tidal change.

Let us consider the plankton once more. As I have shown, the marine and the freshwater plankton in the estuary are both drifting into regions beyond the limit of their salinity range. The consequence is that there is a region without living plankton. As it is known, mostly in the case of rivers, we cannot speak of a typical potamoplankton community because the plankton float downstream too quickly. But in the estuary the change of direction of the currents results in the plankton remaining over a prolonged period in the same water body, floating up and down. This gives the plankton enough time to develop. A small part is always taken away, but this is largely compensated by the remainder multiplying by the same amount as that removed in each tide. The result is quite a series of stable plankton communities typical of a special region in the fresh and brackish-water zones of the estuary.

In this connexion one point may be of special interest: it is not rare to find typical marine plankton in the freshwater part of the estuary, for instance foraminifera and marine diatoms. The reason for this is the difference in the ebb and flood currents. Mostly described in the literature is the high turbidity of the water in the estuaries which prevents the stratification of water levels. Nevertheless the main downstream movement is more at the surface and near the river bed a component of the flood current goes upstream into the river rather than downstream. In this way marine plankton slowly drift far into the freshwater area of the estuary where some of them survive for a time.

This also explains why sometimes marine polychets were found living about 30 miles beyond the upper limit of the brackish-water region, as well as balanids attached to buoys. These buoys give an ideal chance to compare the conditions in the different parts of the estuary, in different seasons and years. In the Elbe they are exchanged twice a year, thus offering the possibility of investigating the settlement of this fouling community on the *tabula rasa* of the buoy. For each species we are able to fix the ecological valence and to relate it to the actual environmental conditions. In a dry year with a smaller outflow of fresh water the brackish-water species penetrate farther up the estuary and, in contrast, in rainy years the upper limit of their distribution is restricted. Sometimes it is astonishing to find barnacles also in the freshwater area. This is explained by the fact that a bubble of salt water had drifted up the estuary, and the included cypris-larvae settled on the buoy: the growing barnacles then survive even if only fresh water now washes this place.

As was demonstrated by the changing conditions in the settlement of the fouling community once more we must point out the instability of the conditions in the estuary. This mainly concerns the poikilohalinity but is combined with the need of a eury-ecology of the whole flora and fauna.

The unstable conditions already demonstrated in the Elbe are greatly magnified in regions of extreme fluctuations of rainy and dry seasons such as are found in tropical estuaries. Day, in South Africa, studied such estuaries which have a barrier towards the sea and become closed for some time. Such "periodically blind" estuaries show a marked change of fauna. The fauna becomes impoverished, but when it regains

contact with the sea and the larvae which have been swept in by the tidal currents become established, the fauna changes completely. This shows that many estuarine animals here have comparatively short lives and must be continually recruited from the sea.

The turbidity of the water in the estuaries develops a high amount of silt. Muddy water obviously limits the depths at which photosynthesis can take place and thus limits the basic supply of plant food. This has been verified in English estuaries. The same situation exists in some parts of the Elbe mouth, and Day noted it in South African estuaries. This concerns the fauna directly. In several cases it could be shown that suspension feeders are absent from the turbid waters. The deposition of mud in some restricted parts may develop anaerobic conditions and a disappearance of bottom animals. This is enhanced in tropical areas where the amount of the decomposition of detritus is increased.

"Blind" estuaries in the tropics show most change in conditions. As soon as the bar closes, tidal effects disappear and the only salinity changes are slow ones due to three opposing factors: the salinity may slowly decrease as the estuary receives more fresh water from the river or from rain and the saline water at the seaward end slowly seeps out through the sand-bar. Or the reverse may happen if evaporation exceeds the inflow from the river and the seepage through the bar, the salinity may slowly rise until the estuary becomes much more saline than the sea. In extreme cases parts of the estuary may dry out completely and form salt-pans. Sooner or later the rains come, the estuary fills up and either bursts its own way to the sea or has an artificial channel cut for it by the farmers whose lands along its banks are being flooded. Then sudden and drastic changes in the salinity occur. In South Africa, nearly all varieties of " blind " or "temporarily blind" estuaries are found.

Day described some quite curious situations in South Africa, e.g., estuaries with reversed salinity gradients: an increase from the seaward end to the upper or more isolated reaches. This happens where evaporation exceeds inflow from the river and the mouth is shallow, so that there is little exchange with the sea. Hedgpeth also described such a type in the Laguna Madre in Texas. It seems that this type must be described mainly as a lagoon type in tropical and subtropical climates.

All these examples demonstrate the typical features of the estuarine type of river mouths and the instability of all hydrographical components: the poikilohalinity is only one of them. This instability is highest in tropical areas where the changes in the seasons produce sometimes absolutely contrary conditions in the estuarine zone of the river.

It must be pointed out that there is still another type of estuaries to be found only in the biggest rivers of tropical areas, an example of which is the Amazon. In spite of a wide open estuary the outflow of fresh water is so high that it overcomes the pressure of the tidal flood from the sea. As a result no sea water enters the river mouth and all brackish-water regions are restricted to the bay outside the river mouth. Nevertheless there is a tidal change far up the river, but this concerns only the change of the freshwater level. It is also known that in the Amazon marine animals penetrate into this estuary, thus suggesting that there is an inflow of salt water near the bottom. Unfortunately, only very little study has been carried out on this tremendously large estuary.

We must now characterize the colonization of estuaries. As has been demonstrated in the Elbe, estuaries are regions of transition and sharp gradients support a fauna recruited principally from the sea. On the other hand, components from freshwater environments are included as well.

It is not appropriate to discuss here long lists of species and to analyse their distribution, but some main characteristics must be put together.

As compared to the sea the number of species is greatly reduced. An estuary is an extreme biotop, but in regions with a good supply of nutrients there may be a large number of individuals. These are eurytop elements living in a wide range of biotops. There are also some specialized species for a brackish-water environment.

At this point it may be of interest to mention a classical study by Annandale in 1922, "The Marine Element in the Fauna of the Ganges". In this paper he expressed the idea that estuaries are "the last refuge of spent races". But as Hedgpeth pointed out in 1957, such a view ignores the importance of estuaries, especially to the economy of neritic subtropical regions, as nursery and feeding grounds.

To survive in an estuary an organism must adapt itself to a wider range of fluctuations in environmental factors than in the sea or in fresh water. Optimum development or successful colonization in an estuary may well depend on the interaction of several factors and as emphasized by Day, the distribution of animals in estuaries cannot be based on any single factor of the environment. The limits of distribution may be controlled by any one of several factors, and excessive variations in salinity, temperature or turbidity often destroy populations in estuaries.

In addition to this type of animal, others became adapted to the fluctuations in estuaries and have found an environment which may actually be comparatively stable. But on the whole this group does not contain a large range of species. Typical brackish-water lagoons or seas show a much richer spectrum of species specialized to this degree of salinity, and it is perhaps doubtful if estuaries have developed a clear, specialized brackish-water fauna at all. However that may be, the greater part of the flora and fauna belongs to euryhaline marine species.

It was pointed out that species of marine origin succeed in migrating into the estuaries, and some of

them may cross the brackish-water regions to penetrate into the freshwater area of the river. It is an old belief that this was easier in tropical regions where there is no difference in temperature between the marine shore and the estuarine water. On the whole it must be admitted that, as far as we know, the tropical estuaries are richer in marine species; perhaps the temperature barrier there is not as high as in colder regions. The estuaries may have been one approach for the transition of marine fauna into limnic biotops. On the contrary, transition of freshwater species into the sea was much rarer.

There is still another biological function of estuaries which must be remembered: the importance of estuaries for migrating animals. First we think of cathadrome and anadrome fishes which pass through the estuary on the way to spawning grounds in rivers or in the sea. The Chinese mitten crab *Eriocheir sinensis* is an example of a migratory species moving into the upper freshwater regions of the rivers but always needing to come back into the brackish-water zone of the estuary for spawning. The utilization of estuaries as nursery grounds is especially pronounced in the middle latitudes where many fishes and such mobile invertebrates as certain species of penaid shrimps and portunid crabs largely depend upon the resources of the estuary for growth and maintenance of their population.

These examples may be sufficient to demonstrate the importance of estuaries as a special biotop between the marine and limnic areas. The study of the estuarine conditions, so complex in the different parts of the world, brings understanding of the conditions in an unstable environment.

During this symposium we are to discuss the geography and biology of delta regions. Initially it seems that the conditions in estuaries and deltas are principally different, but already the various types of estuaries show some relationship to the delta type of a river mouth. One main correlation must be pointed out: a delta consists of many arms of a river opening into the sea, and all these arms build smaller or larger estuaries showing principally the same conditions as stated for estuaries *sensu stricto*. Just as Annandale described in 1922 the immigration of marine animals into the Ganges delta, we also find the same problematics that I have tried to demonstrate for estuaries. Deltas, opening into a tidal sea, show a conglomeration of estuaries, which do not have as wide a range of brackish-water zones as the open estuaries; but the study of such open estuaries may help one to understand the special facts of deltas. Both, estuaries and deltas, are two aspects of the same.

Résumé

La biologie des estuaires (H. Caspers)

Un estuaire se caractérise par l'écoulement libre d'un fleuve dans une mer à marées. Il s'ensuit que les courants de la marée remontent le cours inférieur du fleuve, où l'on trouve toute une variété d'eaux saumâtres abritant à la fois une faune limnique et une faune marine. La faune d'eau douce disparaît brusquement lorsque la salinité atteint 5 ‰ environ, mais certaines espèces marines réussissent à pénétrer dans l'estuaire jusqu'au point où cesse l'influence de l'eau de mer. Quelques-unes sont même capables de parvenir jusqu'à la région des eaux douces du fleuve. Le régime hydrographique comporte des variations saisonnières, liées aux modifications du volume des eaux douces du fleuve (saison des pluies, période des chutes de neige), qui ont des répercussions sur les conditions de vie. Dans l'ensemble, les types d'estuaire diffèrent par la situation géologique, le régime hydrique, l'amplitude des marées et la situation climatique. Certaines conditions caractéristiques des estuaires seront exposées. C'est ainsi que, pour l'estuaire de l'Elbe, on a étudié en détail tout un ensemble de régions d'eaux saumâtres. Au milieu de cette zone, le plancton d'eau douce charrié par le fleuve parvient au point où cessent les conditions qui lui permettent de vivre; il en va de même du plancton marin en provenance de la mer : en conséquence, on trouve là une région dépourvue de toute population de plancton vivant. Un autre fait intéressant est l'existence, dans la zone des eaux douces propres de l'estuaire, de plates-formes de vase *(wadden)* édifiées sous l'influence de la pression hydrographique des marées. Sur ces plates-formes avoisinant les rives du fleuve, on trouve une population limnique spéciale de tubificidés et de chironomidés. Toute la population des estuaires — plancton et animaux vivant sur le sol au fond de la mer (*bodden*) — est marquée par l'instabilité des conditions hydrographiques.

Dans les deltas, la pression des courants de la marée se trouve réduite. Néanmoins, les conditions dans les bras à faible débit du delta sont analogues à celles qui existent dans les estuaires. Mais jusqu'à présent, on n'a pas étudié du point de vue biologique les régions d'eaux saumâtres qui se trouvent dans le cours inférieur d'un fleuve à delta.

Discussion

A. J. DE GROOT. In the Netherlands and western Schleswig-Holstein, it has been found that the diatomae are important in fixing fine sediment. Do those in brackish water and fresh water have the same effect? Diatomae can be abundant in the tropics; are they also important in fixing sediments?

H. CASPERS. Several soil probes have been sent to Hustedt, who found 150 species of diatoms. It has been found that at low tide, in tidal flats, the oxygen saturation may be 180 to 240 per cent.

A. J. DE GROOT. In my institute we have studied the influence of diatoms on the composition of the mud. It has been found they will remove manganese from the mud.

The beneficial influence of diatoms on gaining fine-grained sediments under marine conditions is well known by their action of covering the mud with their gluey decomposition products. Is this also true for fresh-water conditions in the tidal estuary?

H. CASPERS. Investigations on diatoms under fresh-water conditions are still in progress.

Plankton productivity in relation to tropical fish culture

G. A. Prowse

Fish-ponds form a natural part of the scene in the deltas of tropical rivers, and in any swampy area, whether coastal or inland. They can and do contribute appreciably to the food economy of the country, and there is no doubt that in countries deficient in protein they could make an even bigger contribution. The function of a fish-pond is to produce crops of edible fish of marketable size, cheaply, quickly, and without much expenditure of labour. To achieve this the fish-pond must be run with the maximum efficiency, and the ultimate aim, production of fish, must never be forgotten. Unfortunately, the production of fish is often regarded merely as an adjunct to some other process—pig-farming, disposal of waste or sewage, etc.—without any true consideration of the needs of the fish, or even whether there might not be some more efficient and economical way of carrying out the main process. When, as is becoming more and more necessary, fish have to be raised as the principal crop, some of the methods currently used are open to serious doubt. Fish culture, in common with many other branches of agriculture, has often been bedevilled with the use of "standard practices", simply because such methods are traditional. Critical studies of some of these methods have shown that they are in fact far from standard, and are often peculiar to a particular set of environmental conditions, and bear little relation to conditions elsewhere. Obviously the time has come to re-examine all the concepts involved in fish culture, always remembering that the ultimate aim is producing fish as the principal crop.

It is a well-known truism that all animal life is ultimately dependent on photosynthetic organisms. Such plants might be regarded as the primary producers, and in water they may be macrophytic weeds, mainly angiosperms in fresh water, or they may be algae, including the various pigmented flagellate forms. The photosynthetic bacteria, because they usually inhabit environmental conditions unsuited to the growth of most species of fish, might be omitted from this account. In oceans and deep lakes, where the immediate influence of the bottom or the littoral regions may be comparatively unimportant, the primary production consists largely of phytoplankton. On the other hand, in shallow waters such as ponds the macrophytic vegetation may play a dominant role, whilst among the algal components the periphyton and benthic forms may equal or even exceed the phytoplankton in abundance. In such waters the free-floating algae, although usually referred to as phytoplankton, in reality may consist of a mixture of planktonic forms, detached periphyton and benthic forms washed up from the bottom. The presence of macrophytes and the nature of the bottom may profoundly affect the composition of this mixture (Prowse, 1955). For want of a better word it is intended to use the term phytoplankton in this article to describe the free-floating algae, whatever its origin.

Starting with the macrophytes or the algae, it is possible to construct a series of hypothetical food chains culminating in fish. Most of us are familiar with these classical concepts, involving as they do various links such as the invertebrates, be they zooplankton, molluscs or insect larvae, fungi, etc. Useful as these concepts are, they are quite clearly much oversimplified, and many important factors tend to be ignored. Even the short food chains of the herbivorous fish are not as simple as they seem at first sight. The assumption is usually made that all the primary production takes part equally in the conversion into fish flesh, irrespective of the species involved, but this is far from so. Many loose statements have been made on the food of fish, based purely on the presence of organisms in the gut, without any reference to whether they are digested or not.

It is doubtful whether plankton-feeding fish can actively select their food. The most they can do is to swallow all the micro-organisms present in the water, the gill-rakers filtering them out and passing them into the gut. What is important however, is not merely what is ingested, but what is actually digested in the gut. There is now a growing mass of evidence (Fish, 1955;

Prowse, 1955, 1957, 1959*a*, 1961, 1963; Tay, 1961) that the digestibility varies widely between the various groups of algal, classes, orders, families or even genera. The cell contents of most species of diatoms seem to be freely digested by plankton-feeding fish. Among the green algal *Oedogonium* and *Bulbochaete* appear to be digested, but the Chlorococcales not at all. Of the blue-green algae *Anabaenopsis* spp. and *Spirulina* are rapidly digested, but *Anabaena* spp. only doubtfully so, while *Microcystis* is not digested at all. Singh (1961) has claimed that *Microcystis aeruginosa* is digested by *Labeo rohita*, but the evidence he puts forward is most unconvincing. In particular, there is nothing to distinguish the "digested colonies" of *Microcystis aeruginosa* in his photographs from normal colonies splitting open with age, nor has he explained how it is possible to digest the inner cells of a colony without affecting those on the outside. The Euglenineae, so common in Chinese carp ponds, not only are not digested, but have been seen to emerge from the gut alive and still moving. In general it would seem that an unbroken cellulose cell wall is impermeable to the digestive enzymes, and this may explain why *Oedogonium*, with its cell caps easily broken open, is so much more easily digested. Diatoms have pectose walls impregnated with silica, but patterned with a series of perforations, so that enzymes can penetrate easily. Mucilage seems to prevent the entry of enzymes, and this may explain why *Anabaenopsis raciborskii*, with very little detectable mucilage is so much more digestible than *Anabaena oscillarioides* or *A. flos-aquae*, both of which are sufficiently mucilaginous to form quite large flocks in the water. It may also explain the indigestibility of *Microcystis*. On the other hand, there are some species of *Oscillatoria* relatively devoid of mucilage, but which do not appear to be digested, so that the structure of the cell membrane may also be a determining factor. Fish (1952) claims that high concentrations of sodium and potassium ions render mucilage more permeable to the digestive enzymes, and that this is why *Tilapia nilotica* can digest blue-green algae in the highly alkaline Lake Rudolf and not in Lake George. Unfortunately he performed his experiments on *Anabaena cylindrica*, which is not typical of either lake. In Lake George the blue-green algae is commonly a *Microcystis aeruginosa*, whilst the dominant forms in Lake Rudolf are usually *Spirulina* and *Anabaenopsis*. There is also reason to suspect that his cultures may have been infected with fungi, since the method used for purification—antibiotics—was inadequate. In the case of the Eugleninae it is quite clearly the nature of the periplast which prevents entrance of the enzymes, for when this is ruptured by grinding with fine sand, the contents of the broken cells are freely digested. From the foregoing it can be seen that the qualitative composition of the phytoplankton is just as important as the quantitative aspect in regard to the food of plankton-feeding fish.

If the nature of the phytoplankton is of such importance, what are the factors which determine the species which develop in the water, and how can we control them? This a difficult question to answer, since the ecosystem in a fish-pond must be a very complex one, and there must be many interrelationships of which we as yet know nothing. Certain obvious factors, such as of the chemical contents of the pond water, can be studied. Culture experiments, whilst they are valuable indicators of the nutrient requirements of the different plankters, can be misleading if taken in isolation from the natural conditions in the ponds. For instance Chu (1942) gives lower limits for phosphate requirements of diatoms in culture which are far higher than the concentrations normally found in lakes bearing quite a rich bloom of the diatoms. Mackereth (1950, 1951) has shown that diatom cells can take up rapidly enough phosphorus to carry them through several divisions. Studying the nutritional requirements of algae in the ponds is much more difficult, and various workers have obtained inconsistent or even contradictory results. On the other hand, in Malacca, using a Latin Square consisting of 36 ponds of an acre each, it has been possible to follow definite trends in the plankton composition, according to which fertilizer has been used. When, after liming to neutrality, phosphate is the only fertilizer added, diatoms and *Anabaenopsis raciborskii* are two of the dominant species with *Anabaena* spp. and Chlorococcales playing a somewhat lesser role. If potash is added as well, Chlorococcales become a much more prominent component of the algae, whilst the addition of nitrogen, either as calcium nitrate or as urea seems to encourage the development of blue-green algae, particularly *Anabaena* spp. Any addition of organic matter, particularly animal manure, seems to lead to semi-permanent blooms of Euglenineae and often *Microcystis aeruginosa*.

In field experiments it is difficult to assess the effect of the concentration of the nutrients on the composition of the phytoplankton. Because of the influence of the mud, macrophytic flora and the animal biota, the concentration of dissolved ions may appear to bear little relation to the amount of fertilizer. Nevertheless, in Malacca it has been possible to note certain trends. The Latin Square experiment is run as a six-monthly experiment, with a single dose of fertilizer added during each of the first five months. The best crops of fish were obtained with a monthly dosage of 33.6 kg. superphosphate per hectare (30 lb. per acre), when the plankton consisted largely of diatoms and *Anabaenopsis raciborskii*. When the dosage was raised to 44.8 kg. per hectare (40 lb. per acre) the dominant plankton consisted of *Anabaena flos-aquae*, and the crop of fish was lower. It must be stressed that the changes in the composition of the plankton with fertilizer treatment can only be regarded as general trends and not quantitatively exact, but it is remarkable how similar ponds were with the same treatment. Many workers elsewhere have found marked dissimilarity between ponds having the same treatment, but it is almost certain that their ponds were dug out of matured fertile land. Those in Malacca were

excavated in raw laterite and clay, with very little natural nutrients, and almost completely devoid of organic matter. In addition the fertilizer was applied at the surface of the water, in suspended baskets, so that it dissolved in the water.

So far we have dealt with the qualitative aspects of the phytoplankton, but the quantity of plankton is of equal importance, and it is here that there have been so many misconceptions in the past. Prowse (1963) has stressed the interrelation between primary production, grazing intensity and standing crop in fish-ponds. This can be summarized:

Standing crop—Primary producers—Grazing intensity—Mortality

From this it is obvious that the quantitative estimation of the standing crop, in itself, tells us very little. A particular standing crop may be due to a comparatively poor primary production, but with a negligible grazing intensity, or it may be due to a considerably higher primary production with a high grazing intensity. For good fish culture we obviously need a high consumption and digestion of food by the fish, or in other words a high grazing intensity. To maintain this we must at the same time have a high primary production. Primary production, because it is essentially a photosynthetic process, is dependent on light, and for this reason good fish culture should entail the most efficient utilization of the incident light, and this is precisely what many traditional methods of fish culture do not do. Prowse (1963) has shown that in Chinese carp ponds bearing algal scums, light does not penetrate more than 3 inches, whereas in ponds fertilized with superphosphate the plankton is more dispersed and light penetrates almost to 3 ft. Thus the total primary production in the latter ponds is considerably higher than in the Chinese carp ponds. Increasing the density of the plankton in the surface layers may through auto-shading bring about an actual decrease in the total primary production. This has been shown to occur with "overfertilization" (Prowse, 1963; Hepher, 1962) so that although the quantity of fertilizer is greater, the total primary production is less. There is thus an optimum amount of fertilizer to be used. Closely associated with all this is the phenomenon of differential flotation of the organisms (Lund, 1959). In the Chinese ponds blue-green algae with gas vacuoles, such as *Microcystis aeruginosa* or *Anabaena flos-aeris* will accumulate at the surface together with phototactic flagellates such as *Euglena sanguinea*, and thus shade out the less buoyant diatoms. In this way an indigestible scum forms, and the much more useful diatoms are reduced in numbers. This picture may of course be oversimplified, and the true situation may be more complex, but it does in part explain why it is necessary to give supplementary food in Chinese carp culture, whereas in Malacca, in the ponds fertilized only with superphosphate, the same crops of fish are raised solely on the primary production of the ponds themselves.

So far I have dealt with the production of phytoplankton without reference to the macrophytes, but these may affect the situation quite markedly. They may compete with the phytoplankton for the nutrients in the water, so that ponds with heavy weed beds may have virtually no phytoplankton at all. In Malacca it was found that increasing the number of grass carp per pond not only reduced the quantity of *Enhydrias angustipetala*, but also resulted in a considerable increase in the phytoplankton, with a corresponding increase in the growth rate of *Tilapia mossambica*, a plankton-feeding fish. Emergent weeds may suppress the phytoplankton by excessive shading, and so too will dense beds of floating weeds. On the other hand the presence of macrophytes is not always inimical to the production of phytoplankton. Prowse (1955) has noted that in weed beds the density of phytoplankton may be much higher than in the open water, and this difference cannot be explained by wind and water movements. Other workers have also observed this phenomenon, but there has been very little real study to elucidate the cause. Even floating weeds such as *Eichhornia crassipes* and *Pistia stratiotes* need not entirely suppress the growth of plankton, and in Malacca, where the floating mats were not too dense, a considerable number of diatoms, mainly *Navicula confervacea*, were found entangled in the roots. It must be remembered that the percentage of incident light which is used in photosynthesis is quite small, and it is possible that enough light could leak between the floating plantlets to enable the diatoms to grow. No such diatom growths were found under mats of *Azolla* and *Lemna*, where the leaves lie more or less flat on the surface. Prowse (1959*b*) has also shown that the nature of the macrophytic host may affect the species composition of the attached epiphytes. Since these latter when detached may form part of the plankton, the composition of this may in turn be affected. The causes underlying the interaction of the macrophytes and the phytoplankton remain obscure, and they may involve in part thigmotropic effects and in part external metabolites of the macrophytes.

Since this paper is not primarily on fish-culture methods, it is not proposed to go into these in detail. It should be remembered that a fish-pond is an artificial environment, where many of the factors can be controlled. No hard and fast rule can be laid down, but good fish culture should be based on sound limnological concepts: the efficient utilization of light energy, the correct application of nutrients, the production of digestible organisms and short food chains giving rapid energy conversion, the maintenance of oxygen balance, and above all studying the needs of the fish themselves.

Résumé

Le développement du plancton et la pisciculture tropicale (G. A. Prowse)

L'auteur souligne que de nombreuses pratiques piscicoles ne sont pas rationnelles parce que le poisson est considéré comme une ressource « secondaire ». Il réexamine la notion classique des chaînes alimentaires et montre qu'elle est simplifiée à l'excès; puis il étudie la digestibilité de différentes algues. Les diatomées et *Anabaenopsis raciborskii* sont très digestibles, *Anabaena spp.* le sont moins, et les chlorococcales, *Microcystis* et *Euglenineae* ne le sont pas du tout. L'auteur examine ensuite l'influence des engrais sur la composition du plancton. Le phosphate seul favorise le développement des diatomées et *Anabaenopsis*, l'addition de potasse favorise le développement des chlorococcales, l'azote, celui des algues bleues vertes comme *Anabaena spp.*, et les engrais organiques, celui de *Microcystis* et *Euglenineae*. L'excès de phosphate favorise le développement d'*Anabaena flos-aquae*. L'auteur étudie ensuite le phénomène d'arrêt de la lumière par le plancton lui-même et de réduction de la production primaire, en ce qui concerne la pisciculture commerciale aussi bien qu'expérimentale. Il discute l'influence des macrophytes et souligne que certains de ceux-ci peuvent favoriser le développement du plancton.

Discussion

F. R. Fosberg. (1) Even though some algae are indigestible to fish might they not be digestible to copepods or other invertebrates which are eaten by fish?

(2) These are herbivorous fish. If you used carnivorous fish might you not come out the same in the end?

(3) Are there no other organisms which can digest Englenineae and which would provide food for fish?

G. A. Prowse. Rotifera can digest Englena, but this is really secondary production. Each link in the food chain involves an energy loss.

F. R. Fosberg. Why not use carnivorous fish?

G. A. Prowse. Herbivorous fish have a short food chain and give the quickest turnover. A herbivore may grow to 6-7 lb. in six months.

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Fish fauna of the Sunderbans

M. R. Qureshi

INTRODUCTION

In East Pakistan extensive estuarine areas are present in the districts of Chittagong, Bakarganj and Khulna. The Khulna-Sunderbans is the most important and is continuous with that of West Bengal in India. The important feature of the water in the area is that at high tide sea-water enters the distributaries and mixes with the fresh water brought by the rivers, while the conditions at low tide are the opposite. Consequently the salinity changes from time to time. Food is brought by the rivers from the land. The total area covered by deltaic waters is estimated to be about 400,000 acres. The name Sunderbans has been derived from a tree, *Heritiera minor*, locally known as "sundri" which is one of the predominant species of flora adapted for growth in brackish water together with mangrove and other salt-loving plants. The forest is quite thick and harbours the famous Bengal tiger, spotted deer and other animal life.

A survey of the Sunderbans was conducted by Dr. Jenkins in November-December, 1909; Naidu (1953) also made a cursory survey of some portions of this area. The officers of the Directorate of Fisheries have on occasion conducted surveys.

The impact of changing salinity is seen on the fish of this area. Some freshwater fish from the rivers have adapted themselves to the changing salinity, and some sea fish have ascended into this region. The sojourn of the fish is mostly temporary, sea fish arrive at a certain limit and do not ascend higher; similarly, the fish from fresh water only descend to those regions where they can tolerate salinity.

FISH FAUNA

Sharks seem to be the most adaptable. They ascend from the sea and sometimes even reach fresh water. Amongst the elasmobranches the most common are *Carcharias gangeticus* M.N. (more or less a permanent inhabitant of brackish water), *Zygaena blochil* C., hammer-head shark *Pristis cuspidatus* Lathan, sawfish and species of sting-ray (*Trygon* spp.). Amongst the clupeids, *Clupea fimbriaua* (C.V.), *Hisla toli* (C.V.), *Chatoessus chacunda* (Ham.) and different species of *Engraulis* are common. *Hilsa ilisha* (Ham.), the famous hilsa, ascends the rivers for spawning and reaches fresh water. *Polynemus indicus* Shaw and *Polynemus paradiseus* Linn, are common during the monsoon months. The latter is caught in larger quantities near Barisal every year but *Polynemus indicus* seems to remain in saline water and does not ascend higher. The most common species of perch are *Serranus lanceolatus* (Bloch), *Therapon jarbua* (Forsk), *Datnioides quadrifasciatus* (Sevast), *Gerres filamentosus* C., *Cromileptes altivelis* (C.V.) and *Lates calcifer* (Bloch). The last one is the most abundant and prefers brackish water to pure sea-water.

All the three species of pomfret, *Chondroplites chinensis* (Esph), *Pampus argenteus* (Esph.) and *Parastsomateus niger* (Bl.) are common.

Other fish which are commonly caught in the deltaic region belong to the families Chirocentridae, Sparidae, Sciaenidae, Trichiuridae, Carangidae, Scombridae and Mugilidae. The mullets, *Nugil cephalus* L., *Mugil Waigiensis* Q. G., seem to grow faster in brackish water than in the sea.

The fish which have reached this region from the rivers are notably some mullet, cat fish, *Pangasius Pangasuis* (Ham.) and *Silonia silondia* (Ham.), Cuchia eel, *Amphipnous cuchia* (Ham.), *Nandus nandus* (Ham.) and species belonging to the family Anguillidae.

The important prawns which are generally caught there are: *Penaeus semisulcatus* (De Haan), *Penaens indicus* (H. Milne-Edwards), *Metapaeneus monoceros* (Fabricius), *Leander stvliferus* (H. Milne-Edward), which migrate from the sea; and *Palaemon carcinus* (Fabricius), *Palaemon malcolmsoni* (H. Milne-Edward), which migrate from fresh water.

The Gangetic dolphin, *Platinnista Gangetica*, seems to be equally happy in brackish and in fresh water;

similarly, *Crocodilus palustris* and *Gavialis gangeticus* also are of adaptable nature and are common in the Sunderbans marshes and waters.

PREDOMINANT CHARACTERISTICS OF ESTUARINE CONDITIONS

The salinity of estuarine water is less than that of normal sea-water. "The organisms living there must be adapted in one way or another to tolerate this. Further, the salinity varies markedly during the tidal cycle and with the seasons so that a simple adaptation to live at a constant lower salinity is of little use" (Moore, 1958).

Temperature is also important but of secondary character and may show wider tidal and seasonal fluctuations than that of the sea. The increased silt content reduces the illumination and sometimes clogs the gills of animals. The beneficial effects are that large food supplies are brought with the silt.

Many estuaries are greatly affected by effluences from the industrial plants which may adversely affect the animal life. Moore (1958) states that although there are many studies of comparative penetration of organisms into various estuaries, there is less information on the biology of the particular species involved. It has been stated by many workers that salinity is the actual factor involved in setting the upper limitation of penetration of many estuarine species. This fact has generally been assumed without adequate proof.

STUDIES TO BE UNDERTAKEN

1. The effect of salinity on the ascent of fish from the sea into the estuarine zone and the extent to which these penetrate should be investigated. A similar investigation should be carried out on freshwater fish.
2. No work has so far been done on the action of bacteria present in brackish water and their action on the soil found at the bottom. A study should be commenced as soon as possible.
3. Salinity should be worked out at high water and low water and a study made on its effect on fish.
4. A study should be made on the biology of fish and crustaceans normally found in the estuaries in relation to salinity and temperature.
5. Work should be extended later to other organisms, particularly to those which form food for human beings exploited commercially.

Résumé

Les poissons de la région des Sunderbans (M. R. Qureshi)

L'auteur énumère les espèces rencontrées dans les eaux deltaïques du Pakistan-Oriental où, à marée haute, l'eau de mer pénétrant dans les rivières se mélange aux eaux douces. Les variations dans le degré de salinité des eaux influent sur la vie des poissons qu'on trouve dans cette région. Les poissons de mer remontant les rivières ne peuvent pas dépasser une certaine limite. De même les poissons d'eau douce qui descendent des rivières ne peuvent tolérer qu'un certain degré de salinité dans les eaux du delta où ce sont les requins qui semblent s'adapter le mieux à ces conditions changeantes.

Discussion

H. Sioli. Do you know anything about how far marine fish penetrate up the Ganges, for example sharks?

P. Qureshi. I have no record for the Ganges but in other rivers sharks have been seen at dams 120 miles from the sea.

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Fish and fisheries of the Sunderbans

N. Ahmad

TOPOGRAPHY

The southern part of the Gangetic delta lying between latitudes 21° 45′ and 22° 30′ N. and between longitudes 88° and 90° E. is popularly known as the Sunderbans. It includes the major portions of the Bakarganj and Khulna districts of East Pakistan and the 24-Parganas district of West Bengal (India). It is a zone of forests and swamps with innumerable large and small rivers running mostly from north to south. These are connected with one another by a network of cross channels or creeks, locally known as *khals*, some of which still retain connexion with the mother river. One of the rivers, the, Baleswar, is, however, a direct branch of the Ganges which leaves the main stream at Kushtia. This stream keeps the water of the Bay of Bengal fresh for a long distance during the rainy season and the water of the eastern Sunderbans sweet. The force of current and degree of salinity vary from *khal* to *khal* in different months of the year and have a direct influence on the production of phytoplankton which form, directly or indirectly, the food of fish.

The areas left between the streams are usually quite shallow, forming islands. These islands are higher along the banks of the streams than elsewhere, with the result that their central portions are more swampy. During winter months the majority of the islands dry up but during the rainy season they are submerged at every high tide, and pools of water are left here and there. The tides inundate the area twice a day. In the eastern part of the Sunderbans the difference between the high and low level is from 7 to 10 ft. while in the western region the difference is about 16 ft.

By constant tidal action, the water channels continuously receive huge quantities of detritus material washed from the forests. This material provides food, in the form of phytoplankton, for the finny tribe as well as for the crustaceans. The food value of the forest detritus is, therefore, very great.

The water area included in the forest region of the Pakistan Sunderbans is 683.5 sq. miles (see Table 1).

TABLE 1. Water area (in sq. miles) of the forest region of the Pakistan Sunderbans (Khulna district)

Sub-division	Large *khals*, rivers and estuaries	Small *khals*	Total water area
Bagerhat (eastern Sunderbans)	239.6	17.1	256.7
Khulna (central Sunderbans)	213.4	17.5	230.9
Satkhira (central Sunderbans)	179.4	16.5	195.9
TOTAL	632.4	51.1	683.5

The area was once covered by thick forests but as the result of reclamation which started in the year 1830 the district of Bakarganj has been completely cleared and colonized and the forests are now confined to the district of Khulna.

RECLAMATION OF LAND FOR PISCICULTURE AND PADDY CULTIVATION

During high tides the sea-water moves higher up and submerges the surrounding low-lying areas. Such land, therefore, cannot be used for cultivation owing to salinity. People have, however, been busy reclaiming the land in order to produce land crops. This is done by building strong and massive embankments on the banks of the tidal rivers. A *bund* is then raised round the land to be reclaimed. The earth for the construction of the *bund* is taken from the enclosed area and excavation is done in such a way that one or more channels or canals are formed. The impoundment, however, communicates with the stream by one or more sluice gates. In this way certain areas are raised while others

become shallow. For the first few years the enclosed area is used for fish culture. The practice followed is that during the high tide, in the months of April and May when the water contains millions of young fish and prawns, the sluice gates are opened. They are closed during low tide so that the water cannot get out. If a sufficient number of young fish and crustaceans have entered the enclosed area, locally known as *bheries*, the sluice gates are kept closed but in the case of an insufficient number the sluice gates are again opened during high tides. In the mouth of the sluices are placed bamboo traps, which only open inwards. Everything present in the water and entering the *bheries* passes through the traps and is secured, but nothing escapes into the river from the *bheries*. After short intervals the captured fish and prawns are sorted out and suitable ones returned to the *bheries* while the others are discarded. If there is a shortage of fish-food the sluices are opened at intervals to allow food organisms into the *bheries*. The fish and crustaceans are allowed to remain in the *bheries* till they attain marketable size. In this way even during the first year of reclamation of the land the owners earn a sufficient income.

If the owner does not want to keep it as a fishery he does not open the sluices unless it is essential. What he does is to open the sluice for a short time and allow only a small volume of water to enter, sufficient to fill the deep portion of the *bheries* only. During the rainy season when the land is washed and saline water is diluted, he opens the sluice gates at low tides to drain out some water. Successive washings for some years remove the salt and the *bheries* become fit for paddy cultivation. When the fresh water accumulates in the shallow areas of the *bheries* he introduces, for further growth, young *bhetki* (*Lates calcarifer*), mullets and prawns which can live in fresh water. In this way the process has been going on for the last 134 years or so with the result that now in the Pakistan Sunderbans zone alone there are about 200 such *bheries*, some suitable for fish culture, others for paddy and paddy-cum-fish culture.

The more important fish and prawns found in the *bheries* are:

Scientific name	Local name
Fish:	
Lates calcarifer Bloch	*Bhetki, kekti, boar, karal, peteri*
Scatophagus argus Bloch	*Bishtara, paira chanda*
Sciaena cuia Ham.	*Dantina, nuna koi*
Gobius sp.	*Belia*
Polynemus indicus Shaw	*Chela, guchia, gurjaolii, luckiva, sehal, satia, sele, sellet, talia, tarui, bhangan*
Lobotes surinamensis Bloch	*Dora chanda, kot koi, samudra kou*
Eleotris sp.	—
Mystus gulio Ham.	*Gula, nuna tengra, penchgalio*
Mugil parsia Hamilton	*Parsia*
Mugil tade Forsk.	*Bhangan, tarui*
Prawns:	
Penaeus semisulcatus de Haan	*Bagda chingari*
Penaeus indicus H. Milne-Edwards	*Chapda, chapra, chamma, changra, chingi*
Metapenaeus monoceros Fabricius	*Honye, karkaria, karaney, kucho, lallia chingari*
Metapenaeus brevicornis H. Milne-Edwards	*Honye, kaieney, kucho, saga chingari*
Caridina gracilipes de Man	*Ghaen, sunka chingari*
Caridina propinqua de Man	*Ghaen, sunka chingari*

ABUNDANCE OF FISH AND FISH-FOOD

The Sunderbans is an area consisting of hundreds of estuaries and *khals*. These carry enormous quantities of detritus material containing a huge quantity of nutrients, organic and inorganic, necessary for the formation of phytoplankton. The phytoplankton, as we know, serve, directly or indirectly, as food for fish and crustaceans. The shallowness of the estuaries and foreshore permit the penetration of the sun's heat and light resulting in quick multiplication and propagation of phytoplankton. Sometimes the plankton multiply so rapidly that they form a reddish or yellow scum. This phenomenon is due to rapid multiplication of one type of organism by excluding others. Some of the organisms which have been found to produce this phenomenon are peridineans, diatoms and pleurosigma. The reason for its occurrence is that the nutrient material is not lost in the bay as this comes up to the estuaries twice daily due to tidal effect. The heavy rainfall is also responsible for the richness of the fish-food as well as fish fauna.

Another factor is the funnel shape of the bay and the presence of the "swatch of no ground" with a shallow foreshore. The presence of an extensive estuarine area contributes to the dispersal of fish-food by tidal action. The tide makes its appearance near the "swatch of no ground" and travels upwards towards the estuaries.

Another factor responsible for the abundance of fish-food is the washing of decomposed leaves and other vegetation from the forest areas during the high tides.

The Sunderbans area is, therefore, very important from the fishery point of view. The collection made from the Sunderbans revealed the presence of the following species of fish.

Family name	Zoological name	Local name
Carchariidae	*Carcharias gangeticus* Mull & Henle	*Hungur, kamat* (ground shark of the river)
Carchariidae	*Carcharias laticaudus* Mull & Henle	
Amphipnoidae	*Amphipnous cuchia* Hamilton	*Bangas, kuchla, kunche, selach*
Plotosidae	*Plotosus canius* Hamilton	*Gang-jhagur, gang-magur, kani-magur, khagoon*
Pangasidae	*Pangasius pangasius* Hamilton	*Pangas, paungwas*
Schilbeidae	*Silonia silondia* Hamilton	*Bacha, basa, dhain, jilung, shilong, siloin, silond*
Bagridae	*Mystus gulio* Hamilton	*Gula, nuna tengra, panchgalio*
Ariidae	*Arius gagora* Hamilton	*Gagla, gagra, gogat, goghna*
	Arius dussumieri Cuv. & Val.	
	Ketengus typus Bleeker	*Med, meda*
Clupeidae	*Clupea fimbriata* Cuv. & Val.	*Chandana, takya, khair*
	Hilsa ilisha Hamilton	*Hilsa, ilish, ilisha*
	Clupea toli Cuv. & Val.	*Chandana, nurhilsa*
	Pellona elongata Bennett	*Ramgasha*
	Pellona Indica Swains.	
	Raconda russelliana Gray	*Kura phasa, phyasa*
	Opisthopterus tartoor Cuv. & Val.	*Tarture*
	Chatoessus nasus Bloch	*Barang*
	Chatoessus chacunda Hamilton	
	Engraulis hamiltonii Gray & Hardw.	*Phyasa*
	Engraulis telara Hamilton	*Teoach, tel tampri* (anchovy)
	Engraulis mystax Bloch & Schn.	*Phansa*
	Engraulis indicus Hasselt	*Kagaja*
	Coilia dussumieri Cuv. & Val.	*Carialli*
Scombresocidae	*Belone strongylura* V. Hasselt.	*Bara-tunchi*
	Hemirhamphus cantori Bleeker	*Ekthute, gangturi, thute*
Percidae	*Lates calcarifer* Bloch	*Kekti, bhatki, baor, karal, petari, khaibal, khaibai*
	Cromileptes altivelis Cuv. & Val.	
	Serranus Lanceolatus Bloch	*Bhol-karal, bole, hal*
	Serranus sonnerati Lacep.	*Bhetki, sal, karal, chatki, son bhetki,*
	Therapon theraps Cuv. & Val.	*Barguni, jirpai*
	Lobotes surinamensis Bloch	*Dora chanda, kat koi, samudra kau*
	Therapon jarbua Forsk.	*Barguni, jirpai*
	Datnioides quadrifasciatus Sevast	*Bedha, patta, karal*
	Gerres filamentosus Cuvier	*Jagiri, tak chanda, taka chanda, taka maca, takya*
Squamipinnes	*Holacanthus anularis* Bloch	*Dudkamal*
	Scatophagus argus Bloch	*Bishtara, paira chanda* (leopard pomfret)
	Drepane punctate Gmel	*Rupi-chanda*
	Toxotes chatareus Hamilton	
Sparidae	*Crenidens indicus* Day	*Kala khuramti*
	Pagrus spinifer Forsk	*Datina, khuranti*
	Chrysophrys datnia Hamilton	*Kharanti datina*
	Chrysophrys berda Forsk	*Datina*
Nandidae	*Nandus nandus* Hamilton	*Bheda, bhera, boka, chedri, dud-hurkha, gudtha, keana, latha, meni, nandus*
Sciaenidae	*Sciaena cuja* Hamilton	*Dantina, nuna, koi*
	Sciaena coitor Hamilton	*Bhola, digri pao*
	Sciaena sina Cuv. & Val.	
	Sciaena diacanthus Lacep.	
	Sciaenoides pama Hamilton	*Bhola, koi bhola, poa, poma*
	Otolithus maculatus Cuv. & Val.	
	Otolithus ruber Bl. & Schn.	
Trichiuridae	*Trichiurus savala* Cuv. & Val.	*Chaore muchee, rupa patia*
	Trichiurus muticus Gray	
	Trichiurus haumela Forsk	*Churi, rupapatia* (ribbon-fish and cutlass)
Carangidae	*Chorinemus moadetta* Cuv. & Val.	
	Chorinemus Iysan Forsk	*Karsia, mattiamach, taliapara*
	Psettus argenteus Linn	*Chanda*
	Patax teira Forsk	

Family name	Zoological name	Local name
Carangidae (contd.)	*Equula edentula* Bloch	*Tanka chanda*
	Equula blochii Cuv. & Val.	
Gobiidae	*Apocryptes lanceolatus* Bloch, Chiring & Schn.	
	Apocryptes bato Hamilton	*Chiring, rutta*
	Periophthalmus koelreuteri Pall	
	Periophthalmus schlosseri Pall	
	Boleophthalmus viridis Hamilton	
	Eleotris fusca Bloch & Schn.	*Budh baillya*
	Eleotris amboinensis Bleeker	*Bele*
	Gobioides anguillaris Linn.	*Bele*
	Gobioides buchanani Day	*Bele*
	Gobioides rudicundus Hamilton	*Bele, chenna, cheoa baillya*
Mastacembelidae	*Rhynchobdella aculeata* Bloch	*Goichi, kota, baim, tara-baim*
	Mastacembelus unicolor Cuv. & Val.	*Baim, gangregonti, guchi pankal, pankal, haing, turi*
	Mastacembelus armatus Lacep.	*Bam, baim, bamosh, bummi, gont*
Mugilidae	*Mugil speigleri* Bleeker	*Bhangan*
	Mugil tade Forsk	*Bhangan, tarui*
	Mugil ocur Forsk	*Ash bhangan, dangri, khonga*
	Mugil corsula Hamilton	*Arwari, bata, corsula, elanga, halla, hira, ingelee khalla, khor sul, pangdara urul*
Pleuronectidae	*Solea ovata* Richards	*Kantal patta*
	Synaptura pan Hamilton	
	Plagusia bilineata Bloch	*Kukurjib*
	Plagusia marmorata Bleeker	
	Cynoglossus bengalensis Bleeker	*Kukurjib*
	Cynoglossus macrolepidotus Bleeker	
	Cynoglossus hamiltonii Gunth	*Banspata*
	Cynoglossus brevis Gunth	
Tetraodontidae	*Tetrodon lunaris* Bloch & Schn.	*Photak*
	Tetrodon patoca Hamilton	*Boga, palomphatka, photka, potka pakcha, tepa, taptepa* (globe-fish)

PRIMARY PRODUCER

As is well known the people of East Pakistan prefer fish to meat. They welcome fish, if available, with every meal. The demand for fish is, therefore, very great. And the most important district of East Pakistan, not only from the view of fish supply for home consumption but also for export, is Khulna. The people living there catch fish for their own use as well as for sale. From other districts such as Chittagong, Bakarganj and Jessore fishermen migrate and do temporary fishing in this district at suitable places, the most important fish assembly centre in the district being Dubla Island which is located right on the shore of the Bay of Bengal. They start coming in October and continue to work till February or March, depending on the climatic conditions. As soon as the south wind begins to blow the fishermen leave and the island is completely evacuated. According to statistics collected, as many as 65,000 persons come every year to this island in connexion with the fish trade and about 25,000 fishing boats enter the Sunderbans. Throughout the season fishermen catch fish and transport their catches to different places.

PROBLEMS AND THEIR IMPLICATIONS

The greatest problem in the island is the scarcity of drinking water. The water here is saline except at some places where fresh water is found in small quantities near the surface of the earth. Here and there a few depressions are made for the purpose and out of these water is collected with small and shallow utensils. If the depression is made deeper only saline water percolates. This is a problem which requires careful study. To lay pipes several miles long for water supply would be costly and uneconomical; neither would cemented tanks for collecting rain-water serve the purpose for various reasons. Perhaps desalinization of water by some cheap method might be the solution to the problem. At present water is carried by boats over long distances for the purpose but it is hardly enough to meet the requirements.

Another problem is the exploitation of the estuaries. In the year 1908 Dr. Jenkins, a fishery expert from England, used the launch *Ala* to survey the estuaries. The nets used by him were not suitable and the boat was at his disposal for only a short period. There is an urgent necessity to survey the area thoroughly and to

devise some craft and equipment for the exploitation of fish wealth.

So far as the foreshore is concerned no suitable method has been devised for capturing fish from this area. The boats mostly used are indigenous; they take a long time to get to the fishing banks and for the return journey, and there is no suitable arrangement for preserving the catches while in the bay. The result is that the fish are not properly preserved and are spoiled before reaching the markets. The bacteria act rapidly in the humid climate and the fish decompose quickly. The fish which are placed in the sun are not properly preserved because the heat of the sun forms a crust on the surface while the flesh remains green underneath. Due to excessive humidity the fish dried in the sun are not completely dehydrated; the process is also slow. Quick means of transport, more efficient methods of exploitation and scientific methods of preservation are some of the aspects which need consideration.

RESEARCH

Very little information is available about our important food fish. There is a great need, therefore, to carry out research on the bionomics of important food fish in order to avoid overfishing. Dr. S. W. Kemp's communication to the late Dr. Hora on this is very significant:

"This is essential work which cannot be hurried and which obviously cannot be expected to produce early results, but nonetheless I regard it as of primary importance. In it there is enough work to keep a large and well-trained staff busy for a very long term of years. As a beginning I think you should, if possible, start with a small number of carefully selected men working on a few of the most important species. Don't let them get distracted by trying to deal with every kind of fish that comes their way, if they do you won't get anywhere. Much the best method, as we have found over here, is to have one man for each species—the one species is his subject and you will expect him before long to have the most expert knowledge of it, not only of its ecology, but of its distribution and density in different areas, of the ways in which it is caught and of its importance in the fisheries. Later, when the fundamental work has been done and while still keeping a check on it, he can tackle another species. In this way you can of course only deal at the beginning with a small number of species, but you will be continually expanding until in course of time you have a comprehensive knowledge."

As regards estuarine fish Dr Kemp said: "On the estuarine fishes, *bekti*, pomfret, mullet and so forth, it does not seem easy to make specific suggestions. Here again our knowledge is deficient. At least four of your staff should concentrate on these important fishes and with more information it should be possible to find ways for improving the fishery. I would not advocate hatcheries until much more is known, but it might be worthwhile making small-scale experiments in fish-farming in a blind *khal* in the Sunderbans. Experiments in rearing flat-fish are now in progress in a Scottish loch and appear to be promising; the loch is separated from the sea by sluice gates (though this may not be essential) and the water is chemically enriched (see *Nature*, 1944, p. 483). It may be that work on some such lines as these would prove successful in Bengal."

Attention is now being paid to achieve the objects in view. Launches are slowly taking the place of country boats, pilot experiments are being planned to devise suitable craft and equipment for exploitation, ice plants and quick freezing plants are being put up to preserve the fish in good condition. More efforts are, however, needed to reach the goal within a reasonable time.

The successful solution of the above problems is sure to result in improving fish production in the area.

Résumé

Poissons et pêcheries des Sunderbans (N. Ahmad)

L'auteur décrit brièvement la topographie des Sunderbans, qui forment la partie méridionale du delta du Gange, entre les latitudes nord 21°45' et 22°30' et les longitudes est 88° et 91°. Dans le Pakistan-Oriental, il se réduit au district de Khulna.

La différence du niveau des eaux entre la marée haute et la marée basse varie de 2,15 à 4,80 mètres.

La superficie totale des petits et grands « khals », fleuves et estuaires affectés par la marée, dans la région forestière des Sunderbans est d'environ 1 770 km².

L'auteur décrit la méthode appliquée pour la mise en valeur des terres bordant les fleuves à marée, méthode qui a permis de créer environ 200 « bheries » (pêcheries en eau de mer) dans le district de Khulna. Ces exploitations pratiquent la pisciculture, la production de crustacés et la culture du paddy. L'auteur donne également une liste des principaux poissons et crustacés élevés dans ces « bheries ».

Pour des raisons exposées dans le mémoire, les Sunderbans sont très riches en poissons. L'auteur donne une liste des noms scientifiques et des noms locaux équivalents des poissons que l'on pêche dans les estuaires et sur la partie de la côte qui est découverte à marée basse.

On consomme beaucoup de poisson au Pakistan-

Oriental. Quelques indications sont données sur l'île Dubla, qui est le centre d'approvisionnement le plus important du district de Khulna.

L'auteur évoque certains problèmes importants, notamment la pénurie d'eau potable, l'insuffisance des bateaux et des engins de pêche, et le manque de matériel moderne pour la conservation du poisson.

Il souligne la nécessité d'entreprendre des recherches biologiques en vue d'exploiter les pêcheries de façon rationnelle.

Discussion

A. VOLKER. Have you any estimates of the economics of the fisheries of the Sunderbands?

N. AHMAD. I have no figures with me, but they are available elsewhere. Fish is exported as well as used for local consumption.

H. SIOLI. You mentioned opening sluices to flood areas. Is the water fresh or brackish?

N. AHMAD. It is brackish.

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Wood-boring Teredinid shipworms (Mollusca) of mangroves in the Sunderbans (West Bengal)

M. L. Roonwal

INTRODUCTION

General

Six species of Teredinid shipworms [Mollusca, Bivalvia (= Pelecypoda), Teredinidae] have so far been found in the mangrove forests of the Sunderbans (Lower Bengal). Three of these were discovered recently by the Zoological Survey of India.

These shipworms are of considerable economic as well as biological interest. The little that is known about their biology and ecology is summarized in this paper, and a large field of investigation is open for further research. As an example: in a short visit to the Sunderbans I found the shipworm *Bactronophorus thoracites* Gould attacking living trees, and this was the first clear record in the world of a Teredinid borer attacking living trees (Roonwal, 1954*a*, 1954*b*). This finding has been confirmed by surveys carried out in recent years by the Zoological Survey of India, not only for *Bactronophorus thoracites* but also for several other species of Teredinidae in the Sunderban mangroves (see below).

Ecological conditions in mangroves of the Sunderbans

The mangroves are found in the low-lying areas in the Ganges-Brahmaputra delta—on the mainland as well as on the numerous small islands in the estuary. These islands are of relatively recent origin, some having arisen during the last two or three centuries, more or less. The areas are about 5 metres below mean sea level and are submerged under saline estuarine waters for several hours in the spring tides during the six-month period from March to August. The climate is hot and humid, with heavy monsoon rains in summer (June-September). The soil consists of clayey loam or stiff black clay; there is no rock.

The vegetation is of the low mangrove forest type. Two or three species of "baen" (*Avicennia* spp.) form the principal component, and are characterized by the presence of numerous respiratory roots or pneumatophores which grow above ground under the trees up to about 25 cm. in height and are about 15 mm. in thickness. They grow densely, the density varying from 40 to 150 per sq. ft., the greatest density being immediately around the base of the tree. The "orā", *Sonneratia acida* L., produces similar but thicker pneumatophores (Roonwal, 1954*b*). Several other species of trees also occur, viz., "garjan", "gengwā", "goran", "hantal", "keorā", "khālshi", "pāssur", "sundri", and "torā" (or "satali-gāch") (see Table 1). All trees are generally stunted, and many are bent due to heavy storms. Tall grass grows here and there. (For the flora of the Sunderbans, see also Prain, 1903; and the Working Plans of the 24-Parganas Forest Division, 1952*a*, 1952*b*.)

The fauna of the mainland mangroves is identical with that of the adjoining portions of the mainland. The more recent islands are of interest. Thus, in the Lothian and Kankramari islands, briefly visited by me in 1954, the following observations were recorded (Roonwal, 1954*b*, p. 93): "The larger mammals, e.g., the tiger, wild boar and deer ("cheetal", *Axis axis* Erxl.) have already invaded the islands from the mainland. The insect fauna is poor; there are a few species of ants and grasshoppers and no termites. Butterflies and moths were not seen but a few species no doubt do occur. Crabs of two or three species are common."

Teredinids in other mangroves, etc., in India

Ganapati and Rao (1959) found in the mangroves of the Godavari estuary, near Yanam on the eastern coast (Andhra Pradesh), five species of Teredinidae. *Teredo (Dactyloteredo) juttingae* Roch was the most common, while *Bankia (Bankienella) edmondsoni* Nair was also fairly common. *Bankia (Lillobankia) campanellata* Moll & Roch and *Teredo (Teredo) furcillatus* Miller were rare. Other borers were: *Martesia striata* (L.)

TABLE. 1. Species of living trees found attacked by Teredinid borers in the mangroves of the Sunderbans (Lower Bengal)

Family	Botanical name	Local (Bengali) name	Species of attacking Teredinid borers
Euphorbiaceae	*Excoecaria agallocha* L.	*Genwā*	*Bc. thoracites, Bk. (L.) campanellata, T. (K.) mannii*
Lythraceae	*Sonneratia acida* L.	*Orā*	*Bc. thoracites*
	Sonneratia apetata Buch.-Ham.	*Keorā*	*Bc. thoracites*
	Carapa obovata Bheme	*Dhundal*	*T. (K.) mannii*
Meliaceae	*Xylocarpus molluccensis* Roemer (= *Carapa molluccensis* Lamk.)	*Pssāur* or *pashur*	*Bk. (L.) campanellata*
Myrsinaceae	*Aegiceras corniculatus* (L.) [= ? *A. majus* Gaerten]	*Khālshi* or *kulsi*	*Bc. thoracites, Bk. (N.) roonwali, T. (K.) mannii*
Palmae	*Phoenix paludosa* Roxb.	*Hantal*	*Bc. thoracites*
Plumbaginaceae	*Aegialitis rotundifolia* Roxb.	*Torā* or *satali-gāch*	*Bc. thoracites*
Rhizophoriaceae	*Ceriops decandra* Ding Hou [= *C. roxburghiana* Arn.]	*Goran*	*Bc. thoracites, Bk. (L.) campanellata, Bk. (N.) roonwali, N. lanceolata, N. sajnakhaliensis, T. (K.) mannii*
	Ceriops tagal (Perry) Robson [= *Ceriops candolleana Arn.*]	*Goran*	*Bk. (L.) campanellata, Bk. (N.) roonwali, N. lanceolata*
Sterculiaceae	*Rhizophora conjugata* L.	*Garjan*	*Bc. thoracites*
	Heretiera fomes Buch.-Ham. [= *H. minor* Roxb.]	*Sundri*	*Bc. thoracites, N. lanceolata, T. (K.) mannii*
Verbenaceae	*Avicennia alba* Blume	*Baen* (white)	*Bc. thoracites, Bk. (N.) roonwali, T. (K.) mannii*
	Avicennia marina Vier happer	*Baen*	*Bk. (N.) roonwali, T. (K.) manii*
	Avicennia officinalis L.	*Baen* (dark)	*Bc. thoracites, Bk. (N.) roonwali, T. (K.) mannii*

(Mollusca: Pholadidae) and *Sphaeroma terebrans* Bate (Crustacea). The Teredinid borers attack both living trees and dead stumps of *Avicennia* spp. Living trees near the water's edge were severely attacked at the bases 15-25 cm. above and below ground level, while dead stumps were literally honeycombed with the Teredinids. These mangroves occur not only in the swamps contiguous to the mainland but also in the lowly raised islands at some distance from the shore. The vegetation consists mainly of trees of *Avicennia* spp., interspersed here and there with grass. At high tide the roots and stems of trees are submerged with sea-water to a depth of about 30 cm. Nair and Gurmani (1957) found several species of Teredinids at the fishing ports of Tondi and Adirampatnam (east coast, Madras State), but none of the six species recorded here from the Sunderbans was present.

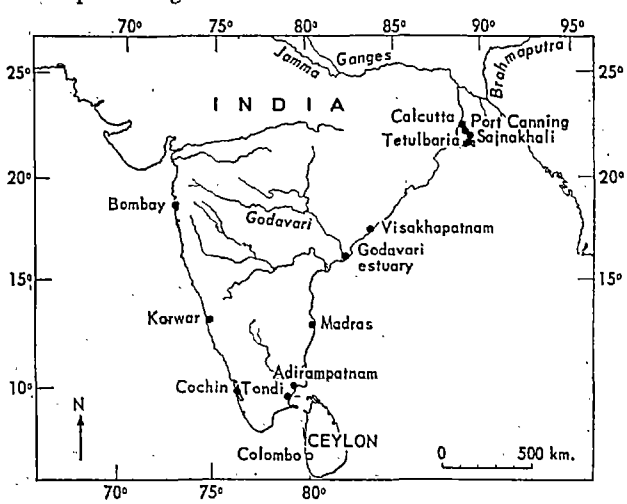


FIG. 1. Map of coast of India, showing the collecting localities of some species of shipworms (Teredinidae).

It is noteworthy that Watson (1928), who made a detailed survey of the mangroves of the Malaya Peninsula and recorded several animal pests of these forests, e.g., crabs, insects and monkeys, made no mention of any molluscan borers.

TEREDINIDS IN MANGROVES OF THE SUNDERBANS

General

The six species found in the mangroves of the Sunderbans of West Bengal are: *Bactronophorus thoracites* Gould, *Bankia (Liliobankia) campanellata* Moll & Roch, *Bankia (Neobankia) roonwali* Rajagopalaiengar, *Nausitora lanceolata* Rajagopal, *Nausitora sajnakhaliensis* Rajagopal, *Teredo (Kuphus) mannii* Wright.

From collections as well as field observations (Rajagopal, personal communication), it appears that in

the mangroves of the Sunderbans, as judged from the Sajnakhali surveys, *Teredo (K.) mannii* is the dominant species. Much less common but still fairly numerous are *Bankia (N.) roonwali* and *Nausitora lanceolata*. *Bankia (L.) campanellata* and *Bactronophorus thoracites* are uncommon, while *Nausitora sajnakhaliensis* is rare. These species are now dealt with in some detail.

Bactronophorus thoracites Gould
See Plates VIII (a) and IX (a).

1859. *Teredo thoracites* Gould. *Proc. Boston Soc. nat. Hist.*, Boston, vol. 6, p. 15-16. Type-locality: "Tavoy, British Burma." [The date of publication of this entire volume appears to be 1859 as clearly given on this title page, and not Oct. 1856 as given by many authors.]
1954. *Bactronophorus thoracites* (Gould) Roonwal. *Proc. zool. Soc.*, Calcutta, vol. 7, no. 2, p. 91-105. (3 plates.)

Characteristics. Whole animal: length, in living condition, may reach up to 25 cm. or more. Shell: large (length about 17 mm.), subglobular, dark coloured, narrowing posteriorly; anterior lobe with about 120 denticulated ridges, number varying with size of specimens; umbones covered by a shelf; apophysis flattened, projecting from umbon and extending one-third the distance towards a large ventral knob. Pallets: stout and long (about 28 mm. or more, depending on size of specimens), stilt-shaped; style long and slightly wavy, with flat smooth inner surface and warty, slightly convex outer surface, blade three-fourths as long as style, thin, linear, obliquely truncated at tips. Siphons: united throughout except at distal end, and with numerous papillae on surface; tips black.

Distribution. From India to Australia.

India. West Bengal (24-Parganas district): mangroves of Shajnakhali and the Kankramari and Lothian islands (Roonwal, 1954*a*, 1954*b*; and collections in Zoological Survey of India). Andhra Pradesh: Visakhapatnam harbour (Nagabhushanam, 1958). Maharashtra: Bombay (Palekar and Bal, 1957*a*).

Elsewhere (Roch, 1955). Burma (Tavoy, the type-locality); Malaysia (Singapore, Wright, 1866); Cochinchina; Indonesia (Sumatra, Borneo); the Mollucas, the Philippines; Ryukyu Archipelago; and Northern and Western Australia.

Ecology. Not uncommon in the Sunderbans mangroves, but evidently more common than *Nausitora sajnakhaliensis*. Common on bottoms of *catamarans* (small country boats) in Visakhapatnam harbour (Nagabhushanam, 1958) but apparently not found in the mangroves of the Godavari estuary farther down the east coast (Ganapati and Rao, 1959, did not record it). Apparently rare in Bombay (Palekar and Bal, 1957*a*, found a single specimen in a beam of teak, *Tectona grandis*, in the Sewree Timber Pond, Bombay).

The first record from India is that of Roonwal (1954*a*, 1954*b*). He found it attacking living as well as dead trees on the Kankramari and Lothian islands (Sunderbans, West Bengal). This was the first clear record of a Teredinid borer attacking living trees anywhere in the world. Subsequent surveys by the Zoological Survey of India field parties in the Sunderbans have amply confirmed the fact that the species infests living trees which externally show no apparent sign of attack. The trunks of the following living trees were attacked in the Sunderbans: "baen" (*Avicennia alba* and *A. officinalis*), "garjan" (*Rhizophora conjugata*), "gengwā" (*Excoecaria agallocha*), "goran" (*Ceriops decandra*), "hantal" (*Phoenix paludosa*), "keorā" (*Sonneratia apetata*), "orā" (*Sonneratia acida*), "khālshi" (*Aegiceras corniculatus*), "sundri" (*Heretiera fomes*) and "torā" (*Aegialitis rotundifolia*). It was also found in the dead standing trunks and logs of these species. The borer is generally found in the basal part of the trunk, up to about 60 cm. above ground of the living or dead tree and also in the tap root, up to about 60 cm. or more below ground level. Living trees, with a crown of green leaves and outwardly healthy, were found riddled with galleries of the borer, and a push by a couple of men often sufficed to fell them. Trees of all girths (15-60 cm.) present were found to have been attacked.

Bankia (Liliobankia) campanellata Moll & Roch
See Plates VIII (e) and IX (e).

1875. *Teredo campanulata* Sowerby. *Conchol. Iconica*, London, vol. 20, "*Teredo*, Plate 2 ", Figs. 9*a-c*. Type-locality: unknown [Not *T. campanulata* Jeffreys, 1860, *Ann. Mag. nat. Hist.*, London, vol. 6, no. 3, p. 127.]
1931. *Bankia campanellata* Moll & Roch. *Proc. malac. Soc. Lond.*, vol. 19, p. 215, Plate 25. [New name for *Teredo campanulata* Sowerby, 1875, *supra* (pre-occupied by *campanulata* Jeffreys, 1860). Type believed to be lost.] Type-locality: unknown. Habitat uncertain, "probably between East Africa and India" (Roch, 1931, p. 216).

The exact nomenclatural position of *Bankia campanellata* has been discussed by Clench and Turner (1946), and the summary of references given above are based on that discussion.

Characteristics. Whole animal: length, in living condition, may reach up to about 15 cm. or more. Shell: rather broad, white; posterior median lobe broad; auricle narrowed at juncture, broadly expanded towards lateral margins, raised in a concave curve above lateral margin and sloping downwards. Pallets: about 30 mm. long; with a stalk and blade, the latter consisting of a series of widely-spaced cones with funnel-shaped calcareous portion; outer margin of periostracum slightly U-shaped and smooth, inner margin flat, lateral margin produced into wide, blunt and upwardly curved awns. Siphons: united throughout their length except at distal end.

Distribution. Widespread in the Indian Ocean.

India. From Lower Bengal, along the east coast up to Madras. West Bengal (24-Parganas district): Port Canning and Sajnakhali forest (Sunderbans) (collections in the Zoological Survey of India). Andhra Pradesh: Visakhapatnam harbour (Nagabhushanam, 1960*a*, 1962*a*, 1962*b*); Godavari estuary near Yanam (Ganapati and Rao, 1959). Madras State: Madras harbour (Daniel, 1959).

Elsewhere (Roch, 1955). Indian Ocean: Reunion Island (off Madagascar); Malaya Archipelago and Indonesia (Sumatra).

Ecology and biology. Rather uncommon in the mangroves of the Sunderbans (West Bengal). Common farther down on the east coast (Visakhapatnam harbour and Madras) but rather uncommon in the Godavari estuary. In the Sajnakhali mangroves, Sunderbans (collections in the Zoological Survey of India) it attacks the trunks of living and dead trees and logs of "gengwā" (*Excoecaria agallocha*), "goran" (*Ceriops* spp.) and "pāssur" (*Xylocarpus molluccensis*); other species are also probably attacked. In the mangroves of the Godavari estuary, living and dead trees of *Avicennia* spp. are attacked, but the borer is uncommon (Ganapati and Rao, 1959).

Its biology and ecology have been studied in recent years in Visakhapatnam harbour by a number of workers, and the results are briefly given below. According to Nagabhushanam (1962*b*) the breeding season is relatively short, lasting from August to the end of February. The author adds that the high temperatures of the harbour waters during March-July (28° to 31.2° C) are probably not conducive to development and settlement of the larvae. It reaches sexual maturity when it is about 12 mm. long. The species is oviparous, eggs being extruded by specimens in sea-water, where fertilization occurs. Growth in larger specimens, as judged by burrow length, is about 42-60 mm. (average 51.5 mm.) per month, the maximum growth (60 mm.) occurring in December. Ganapati and Nagabhushanam (1959) found that, like other species of the genus, *B. (L.) campanellata* also is essentially protandric, i.e., the majority of individuals pass through a functional male phase before reaching the female condition. Fully adult individuals, measuring 100 mm. and above in length, have the appearance of either males or females with no indication of ambisexuality.

From experiments on the settlement of borers on immersed surfaces, Nagabhushanam (1962*a*) concluded that it attacks under a wide range of light intensities but prefers darkness. The larvae settled more readily on the underside of horizontal surfaces than on those of inclined ones. This, according to Nagabhushanam, is due to their habit of swimming upwards as a result of which larvae remained trapped underneath horizontal surfaces but swam round the edge of inclined surfaces. Settlement on wood panels is greatly inhibited by fouling accumulations, clean panels in Visakhapatnam harbour showing as much as eleven times the settlement as compared with the heavily fouled ones (Nagabhushanam, 1960*b*). In test panels at Visakhapatnam harbour, *B. campanellata* was found from August to February, and was completely absent in the summer months (March-July) (Nagabhushanam, 1962*c*).

Bankia (Neobankia) roonwali Rajagopalaiengar
See Plates VIII (b) and IX (b).

1961. *Bankia (Neobankia) roonwali* Rajagopalaiengar. *Sci. & Culture*, Calcutta, vol. 27, no. 11, p. 550.
1961. *Bankia (Neobankia) roonwali* Rajagopalaiengar. *Rec. Indian Mus.*, Delhi. (In press.) Fuller description and figures.

Characteristics. Whole animal: length, in living condition, may reach up to about 38 cm. Shell: about 6-12 mm. long; globular, thin, white to pink; extreme anterior area with sinus and without callus; with 38-56 equidistant dental ridges having denticulated free margin; antero-median portion with 28-32 denticulated ridges; middle part of median lobe narrow; umbon projecting as a knob; auricle extending over median lobe as a shelf. Pallets: about 13-36 mm. long, fragile, cone-in-cone type; with a stalk (about 5-21 mm. long) ending in a blade (7-21 mm. long); 6-13 cones; free margin of membrane covering the cones having pectinate processes all round. Siphons: conjointed, equal, separate subterminally; collar well developed.

Distribution. India only. West Bengal (24-Parganas district): Sajnakhali forest area (Sunderbans mangroves). Maharashtra: Bombay.

Ecology. Is fairly common in the Sunderbans (though less so than *Tredo (K.) mannii*), and attacks the following living trees: "baen" (*Avicennia* spp.), "gengwā" (*Excoecaria agallocha*), "goran" (*Ceriops* spp.) and "khālshi" (*Aegiceras corniculatus*). It also attacks the dead wood of these species as well as that of "pāssur" (*Xylocarpus molluccensis*).

Nausitora lanceolata Rajagopal
See Plates VIII (c) and IX (c).

Nausitora lanceolata Rajagopal. *J. Bombay nat. Hist. Soc.*, Bombay. (In press.)

Characteristics. Description in press.

Distribution. Coast of India. West Bengal: River Hooghly (Kidderpore Docks, Calcutta) and 24-Parganas district (Port Canning and the Sunderbans mangroves at Sajnakhali and vicinity).

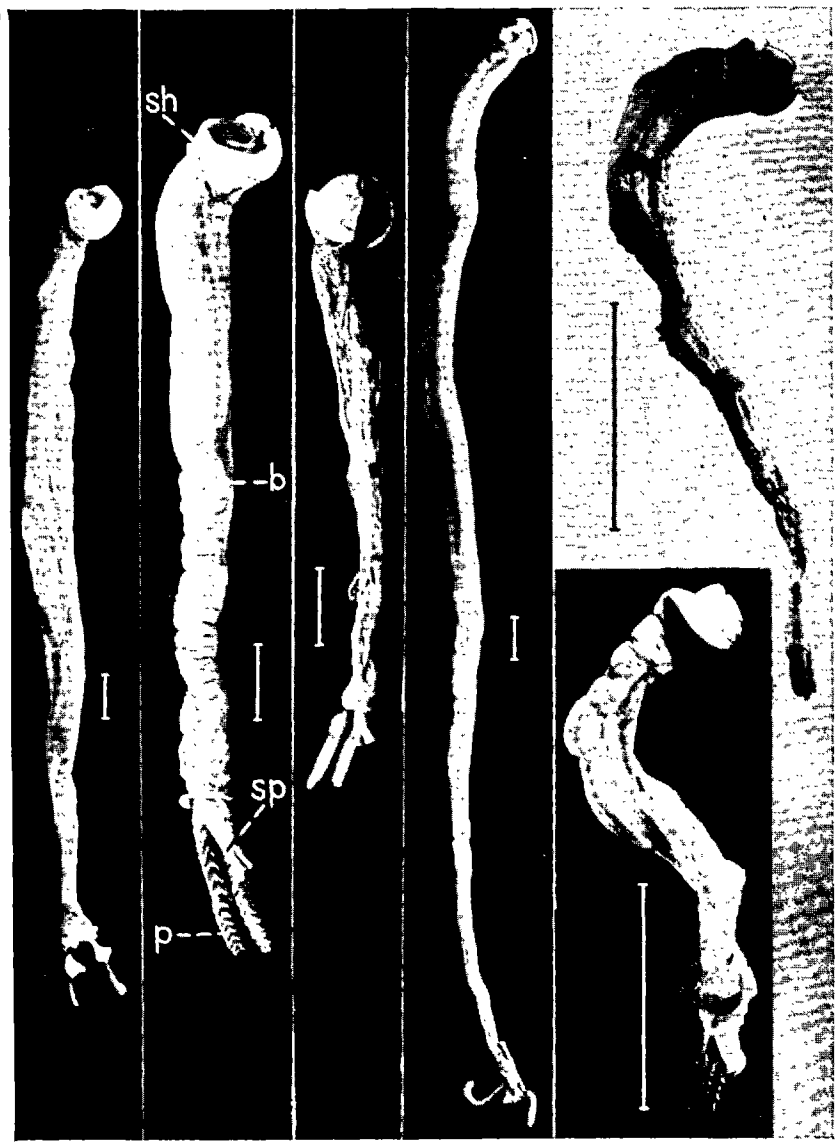
Ecology. Fairly common in the Sunderbans, but much less so than *Tredo (K.) mannii*. Found attacking submerged planks (at the Kidderpore Docks) as well as

PLATE VIII.
Shipworms (Teredinidae) from mangroves of the Sunderbans, West Bengal (India).

(a) *Bactronophorus thoracites* Gld.;
(b) *Bankia (Neobankia) roonwali* Rajag.;
(c) *Nausitora Lanceolata* Rajag.;
(d) *Teredo (Kuphus) mannii* Wr.
(e) *Bankia (Liliobankia) campanellata* Moll & Roch.:
(f) *Nausitora sajnakhaliensis* Rajag.

b = body
p = pallets
sh = shell
sp = siphon

(a), (b), (c), (d)



(e) (f)

Scales to 1 cm.

PLATE IX.
Hind ends of shipworms (Teredinidae) from mangroves of the Sunderbans, West Bengal (India).

(a) *Bactronophorus thoracites* Gld.;
(b) *Bankia (Neobankia) roonwali* Rajag.:
(c) *Nausitora lanceolata* Rajag.;
(d) *Teredo (Kuphus) mannii* Wr.
(e) *Bankia (Liliobankia) campanellata* Moll. & Roch.:
(f) *Nausitora sajnakhaliensis* Rajag.

b = body
p = pallets
sp = siphon

(a) 5 mm. (b) 5 mm. (c) 5 mm.
(d) 5 mm. (e) 1 mm. (f) 5 mm.

living trees of "goran" (*Ceriops* spp.) and "sundri" (*Heretiera fomes*); also attacking wood of "pāssur" (*Xylocarpus molluccensis*) in jetties at Sajnakhali.

Nausitora sajnakhaliensis Rajagopal
See Plates VIII (f) and IX (f).

Nausitora sajnakhaliensis Rajagopal. *J. Bombay nat. Hist. Soc.*, Bombay. (In press.)

Characteristics. Description in press.

Distribution. India only. West Bengal (24-Parganas district): mangroves at Sajnakhali and vicinity (Sunderbans).

Ecology. Found rarely. A few examples obtained from the trunks of living trees of "goran" (*Ceriops decandra*) in the mangroves.

Teredo (Kuphus) mannii Wright
See Plates VIII (d) and IX (d).

1866. "*Kuphus (?) mannii* Wright. *Trans. Linn. Soc. Lond.*, London, vol. 25, no. 3, p. 565, Plate LXV, Figs. 1-8. Type-locality: Singapore, Malaysia ("Western jetty of the Peninsular and Oriental Steamship Company's new harbour of Singapore").

Characteristics. Whole animal: length, in living condition, may reach up to about 90 cm. Shell: rather large (length up to about 20 mm.); anterior lobe large and quadrilateral, with a series of transverse equidistant denticulated ridges; median lobe very large, broader than long, fusing intimately with auricle, the latter scarcely developed; subumbonal blade broad and curved; no accessory plate. Pallets: with a long (about 17.5 mm. or more), stout and a little twisted stalk; blade deeply cupped; a median protuberance or rib dividing the cavity of cup into a flat inner and a convex outer portion; blade solid and dark brown. Siphons: long and free.

Distribution. Widely distributed in the Indian and Pacific Oceans (from east coast of Africa to India, Malaya and Cochinchina, to Australia).

India. Lower Bengal and eastern and western coast as follows (Palekar and Bal, 1955-57*b*; Nagabhushanam, 1958; Daniel, 1959; Nair, 1963; and collections in Zoological Survey of India). West Bengal: Port Canning; mangroves of the Sunderbans (Sajnakhali, Tetulbaria and vicinity). Andhra Pradesh: Visakhapatanam harbour. Madras State: Pulicat Lake and Madras harbour. Mysore State: Karwar. Maharashtra: Bombay.

Elsewhere (Roch, 1955). Indian Ocean (east coast of Africa, Kerimba island, Comoro, Reunion and Madagascar islands, Malacca, Singapore (Malaysia), Cochinchina, Indonesia (Sumatra), New Guinea, Bismarck Archipelago, the Philippines and Australia (Queensland).

Ecology. According to the surveys carried out in recent years (1958-1961) by the Zoological Survey of India in the Sajnakhali area (24-Parganas district, West Bengal), *T. mannii* is the dominant Teredinid in the mangroves of the Sunderbans. It was found to attack the trunks of both dead and living trees of "baen" (*Avicennia* spp.), "dhundul" (*Carapa obovata*), "gengwā" (*Excoecaria agallocha*), "goran" (*Ceriops* spp.), "khālshi" (*Aegiceras corniculatus*) and "sundri" (*Heretiera fomes*), as well as jetties of "pāssur" (*Xylocarpus molluccensis*) (Rajagopal, personal communication; see also Table 1); probably other species are also attacked.

ACKNOWLEDGEMENTS

It is a pleasure to acknowledge my thanks to the following officers of the Zoological Survey of India for their assistance: Dr. H. C. Ray, Dr. A. Daniel, Mr. A. S. Rajagopal and Mr. N. V. Subba Rao.

Résumé

Les tarets (mollusques de la famille des Térédinidés) dans les mangroves des Sunderbans, Bengale-Occidental (M. L. Roonwal)

Six espèces de tarets de la famille des Térédinidés vivent dans les mangroves des Sunderbans (Bengale-Occidental) : *Bactronophorus thoracites* Gould, *Bankia (Liliobankia) campanellata* Moll et Roch, *Bankia (Neobankia) roonwali* Rajagopaliengar, *Nausitora lanceolata* Rajagopal, *Nausitora sajnakhaliensis* Rajagopal et *Teredo (Kuphus) mannii* Wright.

L'auteur donne un bref aperçu des caractéristiques de ces espèces (à l'exception de *N. lanceolata* et *N. sajanakhaliensis*, dont une description est fournie dans un ouvrage de Rajagopal qui est en cours d'impression), de leur biologie et de leur écologie.

Certains de ces tarets s'attaquent aussi bien aux arbres vivants qu'au bois mort, ce qui confirme les observations faites par Roonwal (1954 *a*, *b*) au sujet du térédinidé *Bactronophorus thoracites*.

C'est l'espèce *T. (K.) mannii* qui est la plus répandue des six. Les espèces *B. (N.) roonwali* et *N. lanceolata*

sont encore assez communes; l'espèce *B. (L.) campanellata* est peu répandue; enfin, *B. thoracites et N. sajnakhaliensis* sont franchement rares.

On sait peu de chose de la vie de ces espèces, sauf *Bankia (L.) campanellata*, qui a fait l'objet de certaines études biologiques dans le port de Vishakhapatnam.

Discussion

H. Caspers. Are there some species of trees not attacked by Teredinids?

M. L. Roonwal. Almost all species are attacked.

H. Caspers. How long will the Teredineae survive in the dry, that is if taken out of the water?

M. L. Roonwal. The Teredinids attack dry wood but this is submerged from time to time. I do not know the survival period of the wood remaining completely dry.

F. R. Fosberg. Do the Teredinids have a planktonic stage?

M. L. Roonwal. Yes, they start as planktonic forms.

H. Caspers. How far up the brackish water will they penetrate?

M. L. Roonwal. Quite a long way up.

H. Caspers. How long do attacked trees survive?

M. L. Roonwal. They survive very well under normal conditions, but attacked trees succumb quickly in cyclones.

H. Sioli. Do the local population eat the Teredenids as in South America?

M. L. Roonwal. I have not heard of this.

D. Mueller-Dombois. How extensive is the damage in a mangrove forest?

M. L. Roonwal. It is quite extensive, at a guess about 40 per cent.

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Some important animal pests and parasites of East Pakistan

H. K. Yosufzai

The fauna of pests and parasites of East Pakistan is very rich, hence, it is not possible to describe in a short paper the extensive damage caused by them to life and property. The author has described only those important animal pests and parasites which have a direct impact on the economic conditions of the people of East Pakistan. Some of the pathogenic protozoan and helminth parasites cause severe damage to human life, while a large number of insects and other pests are responsible for widespread damage to their staple food and cash crops.

There are four important pathogenic protozoan parasites in East Pakistan:

1. *Entamoeba histolytica* is the most important human parasite which causes amoebic dysentery. Although it has a world-wide distribution its predominant occurrence in tropical rather than in temperate regions is due to the fact that the cysts of this pathogenic parasite can survive better in a humid tropical climate. In the absence of exact statistical records it is believed that about 60 to 70 per cent of the population in this part of the country suffer from amoebic dysentery. Floods, during the rainy season, have become a regular feature of this region and contribute greatly to the spread of this disease. According to Miller and Gilani (1951), there are cases of non-dysenteric intestinal disorders in the humid tropical regions. Diet has a great influence on the pathogenic nature of parasites. It is believed that high-protein diets are unfavourable for the parasites. Hence, low-protein consumption by the people of East Pakistan may be one of the factors responsible for the wide-spread occurrence of this parasite.
2. *Entamoeba gingivalis* is the cause of pyorrhoea in man. The parasite occurs in the mouth of man, cat and dog. *E. gingivalis* markedly resembles *E. histolytica*. Bass and Johns in 1914 and Barrett in 1915 were the first to demonstrate an apparent relationship between the parasites and the presence of pus pockets between the teeth and gums. Hinshaw (1926) reported the absence of protozoan parasites in normal mouths and the presence of *E. gingivalis* in most cases of pyorrhoea. The percentage of people attacked by this pathogenic parasite increases with their advancing age. Kofoid (1929) reported that 75 per cent or more of people over 40 harbour it. According to Chandler (1956) the disease is spread not only directly from mouth to mouth by kissing, "but also by minute droplets expelled in coughing or sneezing, and by means of drinking glasses, spoons, etc., on which it is evident that they can live as long as a trace of moisture remains". Hence, the disease is very common in humid tropical regions.
3. *Leishmania donovani* is a flagellate parasite which causes kala-azar in man. Kala-azar is a fatal visceral disease accompanied by fever and enlargement of spleen and liver. It has been established that sandflies (*Phlebotomus argentipes*) are the main vectors in the transmission of all forms of Leishmaniasis (Smith, Halder and Ahmad, 1941). "In kala-azar the parasites are widely distributed in the body but the special habitat seems to be large endothelial cells of blood vessels and lymphatics." They are seen in large numbers in the spleen, liver and bone marrow. In the Indo-Pakistani subcontinent kala-azar occurs in Assam, East Pakistan and West Bengal, a region of higher humidity. In recent years due to advancement in the field of medicine the disease has not spread in an epidemic form.
4. Malaria is another major health problem for East Pakistan. The disease is caused by a protozoan parasite of the genus *Plasmodium*. According to a rough estimate, more than half the population of East Pakistan is exposed to it; every year about 50,000 persons die of malaria and 5 million suffer from this disease. Four species of *Plasmodium* are found to attack man in East Pakistan. They are *Plasmodium vivax*, *P. falciparum*, *P. malariae*, *P. ovale*.

The female *Anopheles* mosquitoes are the vectors for malaria, effecting transmission. However, all the anopheline species are not vectors. Twenty-three species of *Anopheles* have so far been recorded from East Pakistan: *Anopheles aconitus*, *A. annularis*, *A. barbirostris*, *A. culicifacies*, *A. fluviatilis*, *A. gigas*, *A. hyrcanus*, *A. jamesi*, *A. jeyporiensis*, *A. karwari*, *A. kochi*, *A. maculatus*, *A. minimus*, *A. pallidus*, *A. philippinensis*, *A. ramsayi*, *A. splendidus*, *A. subpictus*. *A. tessellatus*, *A. theobaldi*, *A. sundaicus*, *A. vagus*, *A. varuna*.

In addition to the above, Quraishi and Talibi (1956) listed the following species: *Anopheles aitkeni*, *A. annandalei*, *A. insulaeflorum*, *A. leucosphyrus*, *A. lindesayi*, *A. majidi*, *A. stephensi*, *A. umbrosus*; but Ameen (personal communication) did not find them during a two-year survey of anopheline mosquitoes in East Pakistan.

Ameen and Shidrawi (personal communication) reported the presence of *Anopheles filipinae* for the first time in East Pakistan.

There are four important helminth parasites of man in East Pakistan. Here I have observed the presence of two types of hookworms: *Ancylostoma duodenale* and *Necator americanus*. Ibrahim and Chowdhury (1962) reported that of the two hookworms *Necator americanus* is predominant in East Pakistan. A report of the Health Survey and Development Committee (1946) suggested 60-80 per cent incidence of hookworms among the population of East Pakistan and West Bengal.

Apart from hookworms, the most common helminth parasites are the pin-worm *Enterobius vermicularis* and round-worm *Ascaris lumbricoides*. About 50 to 75 per cent of the children and a large number of adults are infected by *Ascaris*. Due to the absence of proper survey incidence and intensity of infection data are meagre, but give some insight into the helminth problem of East Pakistan. I am certain that proper studies will reveal a bewildering state of affairs. Lethal cases of helminth infection are few, but the general health of the people of this region suffers a violent shock and they feel tired and weak due to the presence of these parasites in their body. Hence the total man-hours of labour lost due to helminth infection would be enormous.

TABLE 1. Pests of rice in the field and in stored rice

Pest	Genus	Order
In the field		
Rice ear-cutting caterpillar	*Pseudaletia unipuncta* (H.)	Noctuidae, Lepidoptera
Rice swarming caterpillar	*Spodoptera mauritia* B.	Noctuidae, Lepidoptera
Rice-stem borers	*Schoenobius incertellus* W.	Pyralidae, Lepidoptera
	Chilotraea auricilia D.	Pyralidae, Lepidoptera
	C. polychrysa M.	Pyralidae, Lepidoptera
	Sesamia inferens W.	Noctuidae, Lepidoptera
Rice Hispa	*Hispa armigera* Ol.	Hispidae, Coleoptera
Rice bug	*Leptocorisa acuta* Th.	Coreidae, Hemiptera
	L. varicornis Fb.	Coreidae, Hemiptera
Rice leaf-hopper	*Nephotettix bipunctatus* Fab.	Jassidae, Hemiptera
	N. apicalis Mots.	Jassidae, Hemiptera
Rice case-worm	*Nymphula depunctalis* G.	Pyralidae, Lepidoptera
Rice mealy bug	*Ripersia oryzae* G.	Coccidae, Hemiptera
Rice grasshoppers	*Hieroglyphus* sp.	Acrididae, Orthoptera
	Oxya sp.	Acrididae, Orthoptera
Field rats	*Gerbillus* sp.	Muridae, Rodentia
In stored rice		
Rice weevil or granary weevil	*Calandra* (Sitophilus) *oryzae* L.	Curculionidae, Coleoptera
Rice moth	*Sitotroga cerealella* Ol.	Gelechiidae, Lepidoptera
Stored rice borer	*Rhizopertha dominica* Fb.	Bostrychidae, Coleoptera
Red grain beetle	*Tribolium castaneum* H.	Tenebrionidae, Coleoptera
	T. confusum W.	Tenebrionidae, Coleoptera
Meal moth	*Corcyra cephalonica* S.	Pyralidae, Lepidoptera
Saw-toothed beetle	*Oryzaephilus* (Silvanus) *surinamensis* L.	Cucujidae, Coleoptera
Khapra beetle	*Trogoderma granarium*	Dermestidae, Coleoptera
Brown and black rats	*Rattus* sp.	Muridae, Rodentia

PADDY PESTS OF EAST PAKISTAN

Rice is the staple food of the people of East Pakistan and the total acreage under rice cultivation is over 20 million acres. In terms of the 1951 Census Report, loss every year due to insect pests is about 6 per cent of the total production, i.e., about 400,000 tons of grain of the value of 4.8 million rupees (Alam, 1961).

Twenty-eight different pests of rice, including rats, have been reported. The important ones are given in Table 1.

Below is given the nature of the damage and the control measures of some of these pests.

Rice ear-cutting caterpillar (*Pseudaletia unipuncta* H.). The mature caterpillars cut off half-ripe ears of *aman* rice and cause serious damage to the crop. According to Alam (1962*b*) this is the most destructive field pest of rice in East Pakistan since 1955. It also attacks a wide variety of grasses. The appearance and disappearance of the caterpillars are sudden. They are active between dusk and dawn and most of the feeding is done during the night. During the day they conceal themselves under the foliage.

There are five broods each year in East Pakistan. The fourth brood causes the most damage, during the months of October-November. Cloudy weather or a little rain after a long drought gives the ideal conditions for the outbreaks.

They are controlled culturally by burning straw and stubble after harvest, or by sowing early varieties; and chemically by spraying with 0.2 per cent BHC or DDT or dusting with Agrocide-3.

Rice swarming caterpillar (*Spodoptera mauritia* B.) is distributed throughout East Pakistan and generally appears between June and August on *aus*, between April and May on *aman*, and between August and September to mid-October on *boro* crops. The caterpillars feed on leaves and shoots, and sometimes eat down to the base of the plant. There are several parasites and predators which destroy this pest.

Rice-stem borers are a major problem all over the rice-growing area of East Pakistan. The larvae bore into the growing stem and finally feed on the internal tissue of the stem. As a result the continuity of the vascular tissue of the plant is destroyed affecting general growth of the plant. After severe attacks young plants die and older ones do not bear fruit.

The pests breed on paddy from June to November and hibernate in stubble thereafter. There are five broods each year and the *aman* crop suffers the most.

Burning straw and stubble in the field and the use of light traps give partial control.

Rice Hispa (*Hispa armigera* Ol.) is an important rice pest of East Pakistan and appears between February and August. It is regular and common on *aus* but also attacks *boro* and *aman* crops. It causes serious damage in eastern and southern districts of East Pakistan. About 150,000 to 200,000 acres of rice crops are severely affected every year.

Usually young plants are attacked. The damage is done both by adults and grubs. They eat away the green chlorophyllous tissue of the plant, as a result of which the plants become weak. The loss due to these attacks varies from 10 to 65 per cent or more depending on the degree of damage (Alam, 1961).

Rice bug (*Leptocorisa* sp.) The rice flowers and young grains at the milky stage are attacked by this pest. Adults and nymphs suck the juice from the milky grains; the result is empty grains. They are abundant during July-October and breed at that time. For the rest of the period they live on grasses but do not breed.

Rice hoppers. According to Alam (1961) these have emerged as major pests in East Pakistan since 1956. They suck up plant sap. Yield of *aus* crop has been reduced by 20-50 per cent and sometimes even 80 per cent by their attacks. Climatic factors have great influence on their abundance. Heavy, continuous rainfall during the summer decreases their population remarkably.

Rice case-worm (*Nymphula depunctalis* G.) These attack only the swampy fields with standing water in the plot during July-September and they cannot thrive in dry plots. There are two generations on *aman* crops. Sometimes they form green tubes with rice leaves attached to rice plants in the field. They feed on foliage epidermis.

In addition to the various cultural methods, a number of chemical products are also applied to control these pests. In East Pakistan 0.1 or 0.2 per cent DDT or BHC or 0.02 per cent Endrin are usually sprayed. Sometimes Agrocide-3 is dusted for most of the insect pests. The parasites and predators in nature also play their role in natural control of the pests.

For the field rats various poison baits are used. Sometimes physical methods are also used to kill the rats.

For control of stored-grain pests the "godowns" (warehouses) are usually fumigated. "Killoptera", a mixture of ethylene dichloride and carbon tetrachloride in the proportion of 3 : 1 is mostly used.

JUTE PESTS

Thirty-six insect and two mite pests of jute have been recorded by Sharif (1961). Eleven of these are most important in East Pakistan. A definite statement about the extent of damage caused by each species cannot be made as proper surveys of the incidence and distribution of these pests and the damage

TABLE 2. Jute pests

Pest	Genus	Order
Jute Apion	*Apion corchori* M.	Curculionidae, Coleoptera
Jute hairy caterpillar	*Diacrisia obliqua* W.	Arctidae, Lepidoptera
Jute semi-looper	*Anomis sabulifera* G.	Noctuidae, Lepidoptera
Indigo caterpillar	*Laphygma exigua* H.	Noctuidae, Lepidoptera
Jute buprestid	*Trachys pacifica* K.	Buprestidae, Coleoptera
Jute scopula	*Scopula emersaria* W.	Geometridae, Lepidoptera
	Prodenia litura F.	Noctuidae, Lepidoptera
Jute mealy bug	*Ferrisia virgata* Ckll.	Coccidae, Hemiptera
Red spider mite	*Olygonychus coffeae* Neitner	Acarina
White or yellow mite	*Hemitarsonemus latus* Banks	Acarina
	Otinotus elongatus	Membracidae, Hemiptera

caused by them are yet to be carried out. Das (1948) estimated 20 per cent loss of fibre due to attacks of jute semi-looper, jute hairy caterpillar, indigo caterpillar and white or yellow mite in the experimental plots at Dacca. Sharif (1961) calculated a loss of 34,214,596 rupees during 1959 in terms of 5 per cent loss due to pest attacks.

A list of the more important jute pests is given in Table 2.

The nature of the damage caused by some of these pests is given below:

Jute Apion (*Apion corchori* M.) is a stem-borer and a major pest. As a result of attacks mucilaginous substances come out of the injured plants, cement the fibre bundles with adjacent tissue and harden, thus resisting retting. The seedlings may also die. The older plants produce side branches yielding an inferior variety of fibre. The pest is present throughout the season.

Jute hairy caterpillar (*Diacrisia obliqua* W.) is a serious pest of jute in East Pakistan in areas having heavy rainfall. They continue to damage the crop for about two-and-a-half months between June and August when the plants are over 3 ft. high. As a result of the attack plants are defoliated.

Jute semi-looper (*Anomis sabulifera* G.) is a mid-season pest, causing damage for about two months between June and July when the crop is about 2 ft. high. The semi-looper feeds on the apical buds and young top leaves. One caterpillar may destroy up to 10 plants a day by eating their apical leaves. Growth is retarded and side branches are produced resulting in the shortening of fibre.

Indigo caterpillar (*Laphygma exigua* H.) is common in low-lying areas of East Pakistan and attacks young plants; it has not been recorded in crops more than 1 ft. high. The young caterpillars are gregarious and skeletonize leaves. Early-sown jute is liable to more serious attacks.

Prodenia litura (F.) skeletonizes leaves or defoliates plants. It is a minor pest but occasionally it causes serious damage. The pest attacks when the plants are 2-3 ft. high.

Mealy bug (*Ferrisia virgata* Ckll.) is a late-season pest which usually attacks the seed crops. Both nymphs and adults are injurious.

Jute mites (*Hemitarsonemus latus* and *Oligonychus coffeae*). White mites are the more serious. They suck up the sap of plants and cause the fall of leaves and ultimately partial or complete stoppage of growth. The attack is at its peak in the months of June and July.

SUGAR-CANE PESTS

Seventeen major pests of sugar-cane have been reported; there are several stem-borers, shoot-borers, root-borers and sap-suckers. According to Hazarika (1952) the top-shoot borers are the most destructive pests of sugar-cane in East Pakistan. A selected list of the various sugar-cane pests is given in Table 3.

The nature of the damage caused by some of the sugar-cane pests is given below:

Shoot-borers. The caterpillars of the moths bore into the stem of the growing sugar-cane plant from the top shoot. They work gradually downwards boring through four or five nodes and thus destroy the cane. They pupate inside the stem and lay eggs on the leaves.

Bunchy side shoots are given off from the attacked central top shoot in plants attacked by shoot-borers.

Stem-borers. The caterpillars bore into the growing stem of the sugar-cane plant causing serious damage. Both young and growing plants are affected, but the young plants are much more vulnerable and often die as a result of the attack, whereas older plants do not die but the yield of juice is reduced.

TABLE 3. Sugar-cane pests

Pest (genus)	Family	Order	Part damaged
Shoot-borers:			
Scirpophaga auriflua Z.	Pyralidae	Lepidoptera	
S. monostigma Z.	Pyralidae	Lepidoptera	
S. excerptalis W.	Pyralidae	Lepidoptera	
Stem-borers:			
Chilo tumidicostalis H.	Pyralidae	Lepidoptera	
C. simplex B.	Pyralidae	Lepidoptera	
Chilotraea sp.	Pyralidae	Lepidoptera	
Root-borer:			
Emmalocera depressela S.	Pyralidae	Lepidoptera	
Leaf-hoppers:			
Pyrilla perpusilla W.	Fulgoridae	Hemiptera	Leaves
P. pusana Dist.	Fulgoridae	Hemiptera	
Elasmoscelis platypoda Kirby	Fulgoridae	Hemiptera	
Mealy bugs:			
Pseudococcus saccharifolii G.	Coccidae	Hemiptera	Leaves
Ripersia sacchari G.	Coccidae	Hemiptera	Stem
Miscellaneous:			
Anomala bengalensis Bl.	Rutelidae	Coleoptera	Roots
Parastasis rufopicta Westw.	Rutilidae	Coleoptera	Roots
Heleronychus spp.	Dynastidae	Coleoptera	Roots
Asamangulia cuspidata Wlk.	Hispidae	Coleoptera	Leaves
Termites		Isoptera	Stem

TABLE 4. Pests of tea.

Genus	Family	Order	Activity of pest
Arbela dea Swinh.	Arbellidae	Lepidoptera	Bark-borer
A. theivora H.	Arbellidae	Lepidoptera	Bark-borer
A. spp.	Arbellidae	Lepidoptera	Bark-borer
Phassus malabaricus M.	Hapialidae	Lepidoptera	Root-borer
Zeuzera coffeae Nietn.	Zeuzeridae	Lepidoptera	Stem-borer
Laspeyresia leucostoma M.	Encosmidae	Lepidoptera	Leaf-roller
Toxoptera aurantii B.	Aphididae	Hemiptera	Leaf-sucker
Ceronema japonica Mask.	Coccidae	Hemiptera	Leaf-sucker
Eriochiton theae Green	Coccidae	Hemiptera	Leaf-sucker
Tachardia decorella G.	Coccidae	Hemiptera	Shoot-sucker
Paecilocoris latus Dist.	Pentatomidae	Hemiptera	Shoot-sucker
Helopeltis theivora Waterh.	Capsidae	Hemiptera	Shoot-sucker
Disphinctus humeralis W.	Capsidae	Hemiptera	Shoot-sucker
Oscinis theae Lef.	Chloropidae	Diptera	Feeds on leaves
Andraca bipunctata Wlk.	Bombycidae	Lepidoptera	Feeds on leaves
Biston suspenssaria G.	Geometridae	Lepidoptera	Feeds on leaves
Clania destructor Dgn.	Psychidae	Lepidoptera	Feeds on leaves
Acanthopsyche subteralbata Hampson	Psychidae	Lepidoptera	Feeds on leaves
Heterusia lativitta Moore	Zygaenidae	Lepidoptera	Feeds on leaves

Termites. Hazarika (1952) reports: "Sometimes white ants do a great deal of damage to canes, they attack the setts after they are planted and often serious damage is caused which may prevent germination of the setts. When a plant is attacked by white ants the leaves wither and the plant comes out easily when pulled."

PESTS OF TEA

A list of nineteen pests which cause damage to tea plants in East Pakistan (Alam, 1962) is given in Table 4.

I must conclude by saying that the fauna of pest and parasites of East Pakistan has a tremendous economic importance, hence it is imperative that a proper survey organization be created to survey the rich and extensive fauna of pest and parasites of this part of our country.

Résumé

Principaux insectes nuisibles et parasites du Pakistan-Oriental (H. K. Yosufzai)

La faune des insectes nuisibles et des parasites au Pakistan-Oriental est si riche qu'il est impossible de décrire dans un bref exposé les graves atteintes qu'ils portent à la vie humaine et aux biens. L'auteur se limite aux plus importants de ceux qui affectent directement la situation économique de la population du Pakistan-Oriental. Certains parasites pathogènes protozoaires ou helminthiques causent de graves dommages à la santé de l'homme et de nombreux insectes et autres animaux nuisibles ravagent les cultures de subsistance et les cultures marchandes.

On trouve au Pakistan quatre espèces principales de parasites pathogènes protozoaires. L'*Entamoeba histolytica* est le principal parasite de l'homme qui provoque la dysenterie amibienne. On estime que 60 à 70 % de la population de la région en est atteinte. L'*Entamobea gingivalis* provoque la pyorrhée chez l'homme. Une grande partie de la population souffre de cette maladie. Le pourcentage des porteurs de ce parasite pathogène augmente avec l'âge. Le *Leishmania donovani* est un parasite qui provoque le kala-azar. Le paludisme est également très répandu au Pakistan-Oriental. Cette maladie est causée par un protozoaire parasite du genre *Plasmodium*. On estime que plus de la moitié de la population du Pakistan-Oriental est exposée au paludisme, qui atteint 5 millions de personnes et fait 50 000 victimes par an.

Il existe au Pakistan-Oriental 10 espèces importantes de vers parasites de l'homme. En dehors de l'*Ankylostome*, les helminthes les plus communs sont l'*Enterobius vermicularis* et l'*Ascaris lumbricoides*. Environ 50 à 75 % des enfants et un grand nombre d'adultes sont porteurs d'*Ascaris*. Faute d'enquêtes sérieuses sur l'incidence de la maladie et les conditions d'infection, on ne dispose que de rares données.

Le riz est l'aliment essentiel de la population du Pakistan-Oriental. Les dommages causés aux rizières et aux entrepôts de riz par une vingtaine d'espèces nuisibles posent un grave problème alimentaire.

Les principales cultures du Pakistan-Oriental sont celles du jute, du thé et de la canne à sucre. On a dénombré onze insectes qui causent de graves dommages aux champs de jute. Les plantations de thé sont attaquées par 19 insectes nuisibles et celles de canne à sucre par 17 insectes.

L'auteur suggère que l'abondante faune des insectes nuisibles et des parasites au Pakistan-Oriental fasse l'objet de recherches systématiques.

Discussion

H. Sioli. Is there a bilharzia problem here?

H. K. Yosufzai. It is not a major problem. The real problem here is *Enteramoeba histolyca*. It is difficult to obtain accurate information on the infestation.

S. N. Naqvi. Are there any parasites or pests carried by air?

H. K. Yosufzai. It is easy in these days of fast travel for infected persons or diseased plants to be transported, but there are quarantine regulations to deal with this problem. I fear that the rules may not be sufficiently rigorously followed.

A. Volker. Is there anything known about the salinity tolerance of *Anopheles*?

H. K. Yosufzai. Not sufficient is known about this.

S. N. Naqvi. What measures do you have in Pakistan to check the introduction of new pests and parasites from outside the country?

H. K. Yosufzai. We have a Plant Quarantine Department. International health regulations are strictly complied with. However, this does not prevent any parasite that may be harboured by the passengers from coming into the country.

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V

Human influence

Influence de l'homme

Deltas—a basis of culture and civilization

J. Büdel

In the course of history many types of natural landscapes have proved an especially favourable basis for early-developed or highly-developed cultural centres of mankind. In the tropics the wholesome, cool highlands are favourable, especially if there are extensive, flat plains with fertile soils at high altitudes, as are found in Peru, Mexico or Ethiopia. In these days in the ektropical regions the cool areas have favoured such first-class cultural centres, especially those with a favourable climate and fertile soils either near the ocean or near navigable rivers. Such areas are found in Great Britain, along the Rhine and the Ruhr, in the north of France, in Belgium, in the United States as well as in the Soviet Union.

In the succession of such favoured natural landscapes offering particularly favourable possibilities for the early formation and the speedy development of civilization, the deltas at the mouth of big streams flowing into the ocean are playing an important part. It is worth noting that there are also obstructions to the development of the people at an early, pre-technical stage of civilization. As soon as these first stages are overcome, the deltas offer particularly rich possibilities for cultural, economical and political development. Therefore, deltas which previously were not remarkable suddenly advance towards the centre of world culture. It depends on the talents of the population, on immigration or on the changes of international economy and politics because of the dislocation of great traffic routes and of the densely populated centres. It depends also on whether, how, and above all when, i.e., at what moment in the world's history the people began to utilize deliberately all the numerous dormant possibilities. The deltas in semi-arid areas offer the most favourable conditions for early development and even a high standard of civilization. However, at the actual stage of world civilization it should be possible to bring all deltas to the highest possible state of improvement, including those which are as yet underdeveloped.

In the first part of this paper we give a definition of the term "delta". In the second part we examine one by one the unfavourable traits of the deltas as well as those that are especially favourable for the development of civilization. We give examples of how mankind was able, nowadays and in former times, to overcome the unfavourable traits and to utilize the favourable traits with increasing perfection.

These deltas which may be used as a basis for special human development of civilization are extensive alluvions at the mouth of big streams flowing into the ocean. They are only formed if the continent is at rest for a long period or if there is only a slight rise out of the ocean. If there is a quick downward trend (or a quick eustatic rise of the ocean) not deltas but estuaries are formed, like those of the rivers Elbe, Weser, Seine, Loire, Thames, Severn, Congo, La Plata, Amur, Anadyr, Ob and Ienissei.

The accumulation plain of a delta is always built up by the river, not by the ocean. It is always a very extensive, flat, alluvial fan. At the end of the delta the river changes from the steeper fall of its middle and lower courses into the very slight fall of its delta accumulations. On an average the fall is only 1 to 5 cm. for a kilometre (0.01 to 0.05 per mille). Here the river often flows between self-made embankments, but the bends of the river can perforate the embankments at high water. In the delta region, therefore, the river often changes course and direction, but the old channel is not, in most cases, totally abandoned. Usually, the rivers are homogeneous in the middle course and split at the upstream end of the delta into radial arms which split again.

If the ocean is lacking in powerful currents in comparison to the quantities of river water the cleaving of the arms continues seaward: each arm accumulates a neck of land into the ocean. We know this type of delta which looks like the fingers of a spread-out hand as in the case of the Mississippi or, in a less distinct manner, that of the Ebro. But these cases are unusual. Near the

seaward edge of the deltas, the transportation power of the cleaved rivers, which here have almost no fall, usually, loses its energy to such extent that it is overcome by the coastal currents of the ocean. These are then able to accumulate beach ridges and headland bars at the seaward edge of the delta. Thus the delta is bordered by a uniform, straightened shoreline, more or less curving outwards into the ocean. If the space between the two outer arms of the delta forms an angle not more than 60° and if the shoreline is nearly straight (or only slightly curved outwards) the triangle of the Greek letter delta is roughly shaped, from which originated the name given in ancient times to this type of accumulation. Above all this name referred to the classically shaped delta of the Nile. A similar shape is seen in the deltas of the Danube, Volga, Weichsel, Rhône, Orinoco, Niger, Irrawaddy, the deltas of the south Indian rivers Mahanadi, Godawari, Krishan and Kaveri and, with the greatest extension, the united deltas of the two largest streams in this region, i.e., the Ganges and the Brahmaputra. The deltas of the Mekong and of the Lena in Siberia with a similar structure show a shoreline that is somewhat more convex and more curved outwards into the ocean. Another usual type is shown by the deltas of those rivers which, above the real delta lowland, also flow through depressions over a long distance. Here the delta, to some extent, shifts upstream to an extended zone of a marked lower-course character. That is already the case of the Ganges in the lower parts of Hindustan. Classical examples of such long-stretched lower-course deltas are offered by the Indus in Pakistan, by the Euphrates and Tigris in Iraq, by the Po in Italy and above all by the stream richest in water, the Amazon in Brazil. Here the accumulation character of the stream normally restrained to deltas shifts far upstream. If, later, a delta comes into the region of tectonical uplift, the isolated radial arms are able to incise a little. Nevertheless, along those arms the land maintains a delta character in narrow areas but between these there are interfluvial areas which are slightly higher; these are relics of a somewhat higher delta surface which are today "dry islands". That is the actual state of the most extended delta landscape in the world, the Hoang-Ho delta in northern China.

What are the usual unfavourable factors of all deltas and what are those especially favourable for the development of civilization?

The only, but peremptory, unfavourable factors that make the exploitation and cultivation of the deltas very difficult for people in a pre-technical stage of civilization are (a) the utilizable areas in islands being isolated by the arms and (b) the frequency of inundations. Until the people are able to protect themselves from the latter by dams and dikes, deltas remain areas of inferior civilization. In present times this is the case in some ektropical regions, for instance at the mouth of the Lena and in the lower course of the Euphrates and the Tigris. In the tropics there is another aggravating factor: mangrove thickets which increase the isolation of the delta islands. There is an additional unfavourable factor in the tropics: malaria. Isolation caused by mangrove thickets and the dangers of inundation and malaria make many deltas, even nowadays, hostile to settlement. This meeting was convened to consider how these disasters can be parried.

We shall see that the disadvantages of isolation, even of inundation, can be transformed, at a higher stage of civilization, into greatly beneficial conditions.

Inundations have two causes. As far as they are originated by the high waters of rivers, they often occur periodically and seasonally and may therefore be regularly calculated in advance so that people can use them and harness the flow. More dangerous, because they are impossible to calculate, are inundations by the high tides of the ocean: they are produced by stagnation of the spring tide and storm tides. They can appear very suddenly and fall upon people with destroying effects as was the case in 1953 and 1962 on the Dutch and German coasts. Such inundations caused by the ocean have another disadvantage: they bring salt water into the delta and may therefore cause a lack of fresh water in an amphibious landscape.

As soon as man is able to protect himself against the disadvantages of inundation and isolation, against bad water and malaria, then many advantages come to light, often making the deltas into areas of civilization which are of high economic value and which become populated.

The first advantage is the excellent, fine-grained delta soil from which all deltas are built up. There, with such a slight slope, the rivers are only able to transport debris smaller than 100 μ, usually smaller than 20-50 μ. In any case, the clay content ($< 2\ \mu$) is always very high; it makes extraordinary fertile and deep soils. New alluvions from the river in combination with certain technical measures bring about with each high water a renewal of the soil. This is an excellent natural fertilizing process, the most famous example of which is the mud of the Nile in Egypt. Thus it is possible to transform regular, seasonal and river borne freshwater inundations from a disadvantage to an advantage.

The second advantage is the ground-water level which is always high. If clay soil dries up, it clings together solidly, becomes hard and is difficult to cultivate. But if, as it is usual in delta regions, the ground-water level is only a few decimetres below the surface, this disadvantage is easily corrected. In highly developed States, therefore, the delta is the ideal garden plot for choice plants and intensive agricultural cultivation. In the delta region of the Rhine and of the Maas in the Netherlands we find the most profitable horticulture in the world. Irrigation canals lead to each field and flower bed. A handle on the small sluices in such canals is all that is needed for the ground-water level to be

brought precisely to the appropriate depth below whole fields of tulips, tomatoes or carrots. It is possible in this way to regulate the depth at which water is most favourable for the growth at a certain stage. There is no need for artificial irrigation and sprinkling and the supply of drinking water is always sufficient.

Moreover, there is the possibility of artificial irrigation at the surface. This is necessary in delta regions with an arid or semi-arid climate, because the groundwater level there is not high enough during the whole year or at least during the dry and hot season. It is a great advantage that, in a delta, all the arms of the stream flow at the same level as the accumulation plain, and frequently even upon natural embankments above the plain. Therefore it is easy to divert river arms and to direct the water through canals into the fields, as is done extensively in Egypt. Thus the great advantage of intentional, artificial inundation—irrigation—resulted from the danger of inundation and from man having learned three things: to reinforce the natural embankments of the river arms by artificial dikes and dams in such a manner that he is comparatively safe from inundation catastrophies; to lay out a system of canals (with sluices and pumps) outside the dams in the area to be irrigated, which can, in the highest degree, counteract the lack or surplus of water; to calculate with a calendar the periods of seasonal inundations.

We all know that the five nations which make the greatest use of deltas—Egypt, Iraq, Pakistan, China and the Netherlands—have developed these processes in an admirable manner, using different ways according to the circumstances and their respective requirements. They all have been able to transform the original unfavourable conditions of the delta inundations into the greatest advantage for their country—the utmost perfection being achieved by the old Egyptians and the modern Dutch. Herodot said: "Egypt is a gift of the Nile", but one could say even better: "The volition of the Egyptians forced the Nile, the volition of the Dutch forced the Rhine to make their countries become the most perfect cultivated lands of the world".

The fourth advantage is brought about equally by the perfectly plane delta landscape, the vicinity of the ocean and the high wind velocities which are usually found there. These winds bring the great, dangerous storm tides, which so frighten the primitive aborigines. With advanced techniques, however, windmills may be erected everywhere and windmill motors, the latter being especially used for pumps, thus compensating to a certain degree the lack of hydraulic power of the delta arms.

The fifth advantage resides in the nature of the water itself. In the delta area, fresh and salt water mix. The river brings ample oxygen and nutritive substances into the mixing region. Often the result is the enormous abundance of fish, especially in subtropical and tropical regions, for example in the deltas of the Danube and the Volga (sturgeon). The deltas, therefore, always constitute early areas of development for fishing.

The sixth advantage is that the original unfavourable factor, isolation of the delta islands, is transformed into a great advantage at higher stages of civilization, i.e., easy communication by waterways. As opposed to all other natural landscapes in the world, the deltas had excellent communication systems by waterways long before the age of paved roads and railways. There is no need for road maintenance and no necessity to construct ingenious and expensive bridges. Only the simple vessels of inland navigation are needed. There are no big waves like those on the ocean, the smallest boat is safe. Moreover, high wind velocities allow the permanent use of sails, almost as much as on the ocean. In the accumulation area there are no rapids and cataracts, and in the lower course of big streams there is always enough water below the keel, which means permanent and unobstructed navigation even with ships requiring more draught. Advanced dredging techniques are able to overcome the effects of frequent shiftings of the arms. The delta traffic is useful for transporting people, it brings men nearer together and promotes the contrary of social isolation for smaller groups of population: that is to say it creates larger social communities. But traffic on these inland waterways also serves the economic exchange of goods: building materials are imported, most of all the rocks which are lacking in delta areas; wood and artificial fertilizers are also imported and agricultural products of high value, rice, vegetables and cotton, are exported. Thus, in delta regions, as soon as people are acquainted with navigation, larger homogeneous economic districts, which have the same kind of economic interests all over the region reached by the delta, come into existence.

This leads to the seventh advantage, fourfold and perhaps the greatest, including: early concentration of population, division of labour, early prosperity of town life and of political unions and formation of States in delta regions. Here, owing, to the fertile soils with a sufficient moisture content, intensive agriculture and horticulture are made possible even at an early stage of civilization. Even a small land property may maintain a family. This results in a high density of population which soon leads to division of labour: besides the peasantry, which is thoroughly concentrated on agriculture and irrigation, there is another class, that of fishermen and seafarers, then a third, that of the tradesmen, and a fourth, a specially trained class of craftsmen and technicians for the construction of dams and canals, sluices and pumps, ships and windmill motors. Only if cultivation is fully mechanized can the delta make full use of all its natural advantages. Finally and above all these technical efforts require deliberate co-ordination. It is necessary that the construction of dams and canals all over the delta be carried out in accordance with a centralized plan of surveys conducted by leading engineers vested with the appropriate

authority. A strict set of laws governing irrigation is necessary to ensure protection from high waters and storm tides so that all have the same degree of protection or equal benefit from the water. To achieve this end lawyers are needed who are also vested with far-reaching competence. Finally a learned class (originally of priests) is needed to draw up an exact calendar, from the observation of the constellations in the course of the year, to establish sowing and harvest times, high and low waters. One can see that apart from the peasantry many other classes are needed for the maintenance of a highly-developed delta civilization. The far-reaching competence of technicians, lawyers and a learned class call for the early development of a supreme power which was formerly the tyranny of kings who made use of a vast military power and of a civil service. Kings, civil servants, priests and traders at an early stage developed the splendour of luxurious buildings and living, of requisites and worship of the gods. Thus, only the delta regions became endowed with the earliest high cultures of mankind which set a standard in works of art, unsurpassed even today.

We know of four such ancient high cultures, to which—with local variations—all these traits of economical, political and highly artistic development are applicable in like manner. First the Egyptian culture, existing since 3000 B.C. in the delta of the Nile and in the adjacent Upper Egypt Nile valley. Next the Mesopotamian culture in the vast, delta-like riverine oasis of the lower courses of the Euphrates and the Tigris, also existing since 3000 B.C. Then there is the old Indus culture in the Punjab and the Sindh (here also in a delta-like lower-course region), which, likewise, had a decidedly high prosperity period in 2500 B.C. Finally the largest and most homogeneous of these cultures: the northern Chinese one in the gigantic delta of the Huang-Ho which flourished since 200 B.C. at least. This is the only high-culture area in the world which has always regenerated itself since its first prosperity 4,000 years ago. It has kept off or melted down all influence of foreign cultures, was never subdued lastingly by foreign conquerors and is again in present times the centre of a State second in area in the world but by far the greatest in population with nearly 700 million. Of all the four ancient streams and delta areas, northern China's culture was the most continuous and nowadays it still has a far-reaching political organization. In the other three old deltas—in Egypt, Iraq and in the Indus area of Pakistan—kingdoms, empires, religions, even different peoples and languages have repeatedly succeeded one another.

It is common to all these old river-oasis and delta States that they were, if big enough, much more densely populated and had a higher cultural development than the poorer neighbouring regions which surrounded the well-cultivated delta land—deserts, high mountains or woodland of difficult access. The bigger deltas, therefore, were always the centre of large empires. The smaller deltas, on the contrary, were originally regularly inclined sections of larger States whose centre would be farther inland, provided it were fertile enough for higher cultural development. Such inland States always reigned over the streams flowing down, through the State, to the river mouth, even if there were only small deltas.

However, in some few, and therefore most striking, cases even small deltas were successful in shaking off political power from the inland State and in founding separate powerful, small-delta States. It is characteristic of all these small-delta States that they still persisted in maintaining close economic contact with the neighbouring inland States. Through this contact they derived wealth which allowed them to keep military and political independence. Such influential small-delta States were never based on the tyranny of a king, but always on the aristocratically organized *bourgeoisie* of wholesale merchants. The independence of small-delta areas on the border of neighbouring large inland States has always been possible only because this aristocratic *bourgeoisie* was determined to make the best of the three other advantages detailed below.

The eighth advantage is the change from mere fishing and river traffic to sea navigation and maritime trade. On it was based the prosperity of the Netherlands in Amsterdam and Rotterdam, in the Rhine and Maas deltas, as well as of Antwerp on the Schelde river in Belgium. The head of the principality and the shipowner amass capital and have a better view of general political situations than the inlander. Therefore they are able to distinguish favourable political situations for setting up their maritime State. Such a solidarity developed especially in the Netherlands through the common interests of agriculture, trade and navigation and by joint labour at dikes and sluices. Besides, free access to the world created a notable desire for independence as the most powerful motive for political agreement. Thus did the Netherlands become independent from the Hapsburg empire in Germany and Spain after a long-lasting struggle for freedom from 1570 to 1650; and Venice in the lagoons of the Po delta became a sea-ruling State beside all the empires that established themselves since the Roman Empire up to these days on the Italian soil. Venice, was during nearly fifteen hundred years (A.D. 452-1866) a delta-town State, independent from the rest of Italy and in many ways inheriting an especially unadulterated antique culture. Similarly, Danzig in the delta of the Weichsel was from A.D. 997 to 1945 a delta republic, more or less independent from the empires. Town-States in the deltas of Mediterranean rivers are unpretentious examples found in antiquity, such as Thessaloniki (the actual Salonika), or Massilia (the modern Marseille) on the delta of the Rhône.

The importance of these two examples of the Netherlands and Venice is not conceivable without some expan-

sion of the advantages offered by easy maritime trade, i.e., by creating a powerful naval force as well as a merchant marine, which can protect the latter from foreign powers and piracy, and by obtaining independence in world politics with its assistance and by the foundation of the trade-expanding and market areas for the permanent benefit of the home State. If the State's land were lost in war to another power it still existed in its navy. In 1570, the whole of the Netherlands was conquered by the Spaniards but the "Geusen" ruled the ocean with the navy and reconquered in 1572 a small harbour, Briel, at the mouth of the Rhine. This unique occurrence in the world was conceivable only because of the solidarity, the desire for independence and freedom which governed this small-delta State and which achieved much within the next three generations. In 1572 the whole free Netherlands were nothing but a navy without a country and with only a tiny naval base; in 1660 the Netherlands were in possession of the largest colonial empire in the world. Venice, during centuries, played the same part with its numerous colonial bases in what was the ocean of the Middle Ages: the Mediterranean Sea, and even Danzig, in the narrow region of the eastern Baltic Sea, retained a similarly respected independent political and military position.

Another advantage made possible the ocean-expansion of those delta-town States. Because of the natural conditions of the deltas the naval warfare could be carried into the delta to a certain degree. The small sea-going battleships of earlier centuries were often able to operate undisturbed and to support their own, small ground forces along the big streams of the delta. Thus, the besieged town of Antwerp, in the mouth of the Schelde, for a long time received supplies brought by the Dutch from the sea side. Even more important were those last means resorted to for eliminating an enemy coming from the land: destruction of dikes and sluices and artificial inundation of their own soil. The Dutch have successfully made use of these desperate but effective means in many struggles for freedom.

We now come to the conclusions. Delta areas obstruct the development of human civilization at a pre-technical stage. But if the people are determined to use the ten latent advantages for developing techniques at the appropriate time, deltas afford vast possibilities for the development of civilization. Today, our techniques are far more advanced than those in the former centuries, but it remains to be seen if we have the energy to realize and to make use of these vast, up to date unused, advantages in the many undeveloped deltas of the world. In each delta different means are needed to achieve this task, according to its natural outfit, its position and its population. It is very important to call forth the most suitable conditions for this utilization through scientific researches.

Résumé

Les deltas : une base de la civilisation humaine (Julius Büdel)

Les deltas constituent un type de paysage naturel qui a opposé certains obstacles au développement culturel lors d'un état antérieur et prétechnique de la population : inondations fréquentes, isolement des espaces habités par des bras de rivière, eaux souterraines salées, paludisme dans les tropiques, etc. Mais à partir du moment où l'on a surmonté ces premiers âges prétechniques, en particulier dès que l'homme a appris à se protéger des flots de haute marée et des crues de rivière et qu'il a su évaluer les inondations annuelles, les deltas offrirent à l'humanité des possibilités particulièrement favorables de développement culturel, économique et politico-social précoce et intensif.

La première partie de l'exposé décrit la nature des deltas et des différents caractères qui résultent de la séparation des rivières en bras isolés.

La deuxième partie du rapport décrit les nombreux traits particulièrement favorables qui, au cours de l'histoire, ont permis à l'homme de faire des deltas des centres de culture présentant un développement particulièrement intensif. A savoir : le bon sol à grains fins; les eaux souterraines au niveau constamment haut; la commodité d'irrigation artificielle, l'amendement par les apports de limon, l'approvisionnement facile en eau potable, non salée; la grande puissance du vent, constamment présent dans le pays plat et au voisinage de la mer, qui permet l'installation de ventilateurs remplaçant la force hydraulique absente; les possibilités nombreuses de pêche dans la zone de transition entre les eaux douces, riches en éléments nutritifs, et les eaux salées, pauvres en plancton (en particulier dans les tropiques); la création de grandes unités sociales de même caractère économique, grâce aux relations établies entres les îles du delta par le trafic fluvial; la forte densité de population, le développement de la culture urbaine et la formation d'états socialement divisés qui en sont la conséquence.

Dans les grands pays de vieille civilisation où se trouvent des deltas (ancienne Égypte, ancien Irak (Sumer, Assir, Babylone), l'ancien Empire des Indes au Pakistan et le cœur de l'ancienne Chine dans le

delta du Houang-Ho), de tels États avaient constamment un régime monarchique et souvent étendaient leur puissance sur des régions voisines moins favorisées.

Non seulement de grands États ont pris naissance à l'intérieur du pays, au bord des grands fleuves, mais d'autres puissances fondées sur le commerce maritime ont pu, au cours de l'histoire, se développer dans les petits deltas. Ce n'étaient pas des monarchies, mais des républiques. L'exemple en est donné par les Pays-Bas, dans le delta du Rhin et de la Meuse; la République de Venise, dans la région du Pô; Dantzig, dans le delta de la Vistule, et, dans l'antiquité déjà, Massilia (aujourd'hui Marseille), dans le delta du Rhône. Ces États libres s'appuyaient de ce fait sur trois autres avantages que la nature du delta leur offraient : la possibilité d'installation de bons ports maritimes et le passage du trafic fluvial au trafic maritime; la possibilité de fonder, à partir de là, des colonies de commerce d'outre-mer avec l'appui de leur propre flotte de guerre, la possibilité d'augmenter leur propre force de défense maritime par un appui d'outre-mer contre un ennemi attaquant de l'intérieur du pays, ainsi que la facilité d'inonder intentionnellement certaines parties de la région du delta pour arrêter l'invasion ennemie.

A notre époque, tous ces avantages restent inexploités dans de nombreuses parties du monde, en particulier dans les régions tropicales.

La technique actuelle nous offre des possibilités jusqu'ici ignorées. Chaque delta nécessite selon son équipement naturel particulier, sa situation et ses habitants, l'emploi d'autres moyens d'exploitation. Il s'agit donc de trouver par des recherches scientifiques les conditions exactes favorables à l'exploitation des deltas.

Discussion

KANOK PRANICH. I should like to ask whether people came to settle first in the deltaic areas or first in the hinterland, moving down later to the delta?

J. BÜDEL. People settled down in the hinterland first; later they acquired more knowledge of how to handle floods and how to live with them and with the other environmental problems of the delta; then they moved down to these areas more and more.

Influence of man's traditional activities on soils and vegetation

H. Boesch

A well-known though outdated definition of "geography" says that the substance of geography is the study of nature's impact on man—hence the expression "the geographic factor", meaning the total of nature's influences on man. This simple one-way relationship was studied later and it was recognized that the relationship also existed in the reverse sense. The situation could best be circumscribed in the following way:

$$\text{Nature} \rightleftarrows \text{Man}$$

In the anthropological literature it is stressed that in primitive civilizations this relationship functions primarily from left to right, and that with increasing development of technical knowledge the direction is gradually reversed. This statement, though of a trivial nature, can undoubtedly be accepted as correct.

In the programme of this meeting the author has been assigned to enhance man's influence on soils and vegetation with the further restriction that only the traditional activities in the deltas of the humid tropical zone should be considered.

Apparently, traditional activities in these areas are meant to be those which date back into the past and were carried out without modern technological knowledge and its applications. From what has been stated above we may conclude that generally, under such circumstances, man was more strongly dominated by and subjected to the forces of nature than taking the initiative to correct and adjust the natural factors so as to suit his activities.

Therefore the change-over from traditional activities to modern agricultural pursuits means more than mere technical progress since it essentially changes the relationship between man and nature. An example from the rice-growing countries of monsoon areas in Asia will illustrate this point.

The most important controlling factors in rice growing are (a) the distribution and the amount of rainfall and (b) the resulting rise and fall of the rivers and the ensuing inundations.

Rice is a plant with an astounding degree of adaptability to various growing conditions and, through selective breeding over generations, traditional agriculture has produced thousands of varieties which are adapted to different local conditions. Within a distance of a few metres growing conditions may vary considerably, especially with respect to the depth of floodwater, length of period of inundation, etc. In any one village many different varieties of rice have been grown for generations and the farmers know exactly in which locations they are to be used. Usually, one of the first aims of modernized agriculture in these areas consists in controlling the water. If this is done efficiently, it will result in levelling off the differences such as described above and provide standard conditions over a large tract of rice-field in every respect, namely, controlled water level, regulated irrigation or inundation; it will also standardize the varieties of rice to be planted. The latter, in turn, may—not infrequently—bring about difficulties regarding the marketing of the product, because traditional practices have created a market for certain varieties of rice which may not be ready to switch over to a new and more standardized crop. Therefore, with the change from traditional to modern agriculture, much more is involved than mere changes in agricultural techniques or the construction of an integrated river control system.

If, in the assigned topic, only man's influence on soils and vegetation is to be considered, it means that we must be restricted to and concentrate upon two elements or component parts of the natural environment. *A priori*, it may be expected that in a traditional form of agricultural activity man's influence upon these elements may be small.

We believe, however, that closer inspection will reveal in many areas that man's influence has not been as negligible as may be assumed by deductive speculation. Unfortunately, not many detailed field studies

have been carried out by geographers in delta areas of humid tropics. Since we are assembling in Dacca, it may be appropriate to call attention to the excellent series published by the Department of Geography of the University of Dacca under the direction of Professor Nafis Ahmad, and in particular to a study on *Land Use in Rampal Area* (Monograph No. 1) published in 1961.

The Rampal area is downstream from Dacca on the right bank of the Dhaleshwari river and consists of eleven villages, convering a territory of about 9 square kilometres. The population numbers approximately 5,000.

The natural topography and the material, partly stream deposits and partly sea deposits, are typically conditioned by water. Closer investigation reveals, however, that the details of topography are man-made. To quote the original (p. 7): "The topography presents a terrace-like pattern and is largely man-made. It seems that a general difference in level existed from the very beginning and human hands accentuated the differences by raising the higher lands and deepening the lower parts. Today five levels are generally found." In the local language there is a specific name for each level, and each level experiences in a normal year a certain period of flooding and a certain depth of flood-water. Consequently each level occupies a characteristic place in crop production and generally in land utilization. By transforming the surface of the original terrain into terraces, identical flood conditions are created by man for a larger area.

At the same time uniform conditions on any one level but differing from the next bring about the development of a particular soil body for each level. The lowest is generally covered with loamy clays, the next, about 5 to 6 feet above the lowest, with silt, and so on. In a similar way the chemical and physical properties of the soil change with the level. Soil erosion, particularly at the edge of the man-made terraces, is a serious problem which becomes more serious on the higher levels covered by water only during exceptionally high floods.

This excellent study points the way in which further studies might be directed. It also calls our attention to the following principle: traditional activities were not able to cope with the changes of river level; the river was the supreme master, and man's activities were subjected to it. About the only possibility for an adjustment consisted in adapting the topography to create within a village area a number of areas possessing identical flood conditions, hence identical agricultural possibilities. It resulted in the development of different soil types on different levels owing to natural as well as cultural factors. The study mentions also the various ways in which these soils undergo further changes through selected manuring.

Similar observation was made of the terraced terrain in villages north of Dacca. While the population of Rampal is primarily engaged in horticultural activities, rice is the major crop in these villages. In rice cultivation it is particularly important to maintain a given depth of water during the various growth periods, and consequently terracing is of utmost importance, with all the ensuing effects.

As regards soils, therefore, special emphasis in field studies should be placed on evaluating man's part in shaping the local topography and studying the development of different soil types on different levels as a function of varying natural and cultural conditions.

What we can say at the moment about the vegetation is even more insignificant. A look at a land-use or population map, say, of South-East Asia, reveals that there is a contrast between the alluvial plains and deltas on the one hand and the hills and mountains on the other. The latter areas, which are sparsely settled, if they are used agriculturally at all, are extensively cultivated, since shifting cultivation is the prevailing form. The vegetation is either natural or secondary as a result of shifting cultivation.

In the lowlands, plains and deltas, the population density is high. The land was converted a long time ago from natural vegetation to crop land, tree culture, etc., and has been used continuously for agricultural purposes. There is practically no soil erosion, and the soils which may be called young soils are continuously enriched by floods and irrigation.

Therefore man's influence on vegetation consists primarily in the fact that he destroyed the natural vegetation completely. Its original state could be reconstructed only through careful botanical analysis. Furthermore, he introduced cultivated plants, though the problem is not within our present assignment. Thirdly, he may abandon some of this choice land for certain reasons, and a secondary vegetation cover may grow up.

The latter case is exemplified by the placer tin-mining areas of Malaya. It has been carefully analysed and the results published in the *Journal of Tropical Geography* in a number of articles by the geographers working at the universities of Kuala Lumpur and Singapore. There, some of the alluvial level land may be used either for agriculture or for the mining of tin. While the agricultural use takes continuing benefits from the soil, placer mining destroys its agricultural value leaving a country dotted with ponds and sand heaps, totally unsuited for any form of agricultural pursuits and quickly covered with a secondary vegetation of no value.

Finally, there exists a zone where the natural vegetation has been preserved and where agriculture may be extended only with the help of modern technology. It is the case at the outer margin of the deltas near the coast where tidal action and brackish ground water limit the possibilities under existing technological conditions. Here, it may be possible to study the effects of man's influence upon vegetation wherever re-

clamation projects are undertaken. Examples can be found in this country all along the sea coast of the delta.

Following these remarks on actual examples, we would like to add some more remarks on the principles of such investigations from a geographical point of view.

The history of science teaches us that one of the greatest advances occurred in classic Greek times when the observed facts were put together in a rational way into an operational model. Today the word "model" has come into fashion again. Objects of complex nature which were hitherto studied mostly by descriptive methods are transformed into models that can be analysed as to their constituent parts, working mechanism, etc. Of the numerous advantages of such a procedure, the following may be mentioned:

1. A model which consists of such clearly defined parts, functions, etc., can be studied by the methods of modern scientific research, primarily by analysis and synthesis.
2. With such a model the individual elements can be measured and the measurements be recorded in one or more systems, if necessary.
3. If the model is complete, we can use it for experimental purposes and study the influence that any change of any one parameter might bring upon the functioning of the whole and upon the values of the individual parts.
4. Operation with such a model is now made possible for adaptation to such modern research methods as electronic data recording and processing.

The model with which we work in geographical research is called the "geosphere" or the "geospheric model", and embraces the following:

1. The elements or constituent parts of the various spheres that makes up the object of geography. They belong to the litho-, pedo-, hydro-, atmo-, and biosphere, and—as soon as we proceed from the natural to the cultural landscapes—the anthroposphere.
2. The functions which the various elements exercise upon the others. In contrast to other functions which are not considered here, they operate within the elements at any one site; therefore, they will be called intra-functions or intra-functional relations.
3. The natural and cultural factors that influence the geosphere from outside.

The model *sensu stricto* consists only of the first two sets of parts, namely, the elements and the intra-functions. The natural and cultural factors are the steering mechanism. By changing the respective values we induce certain changes within the model.

As long as the anthroposphere does not enter into our model, i.e., as long as we work under natural conditions in a natural landscape into which man has not yet entered, any factoral change will result in a chain reaction of certain changes in the model which follows a path established by the law of cause and effect. The methods of work are strictly within the field of the natural science.

If, on the other hand, man becomes active as an agent and human factors influence the working of the model, the situation becomes basically different and more complicated. The first thing we should realize is that we are now leaving the field of strictly scientific reasoning and that we have first to agree upon certain philosophical principles to which we shall adhere. The most important of these is the question as to whether man has an independent mind or is wholly determined either by forces of nature or by others, such as God, for example.

Determinism was the dominant philosophy in geographic thinking during certain periods. For Carl Ritter it was mostly the will of God, and for Friedrich Ratzel the impact of nature. The latter's was the most important school for many years and his influence on American geographical thinking during the period of environmentalism was considerable. Today such a philosophy is considered outdated and man enters into the operations with the model as something *sui generis*, i.e., with a will of his own and facilities to make his own decisions.

This point is stressed here because it limits to a certain degree the application of the modern electronic operations of the model as mentioned above. The point may be debated later whether it is more advantageous to evaluate man as has been done in the traditional way of anthropological research, namely, to let our own brain serve as a control check by continuous thinking and evaluating, or to put him before a computer and see what the outcome will be. Whatever the result of a discussion might be, the model as such serves the purpose of bringing order into our thinking, with or without a computer.

First, it helps us to classify the different landscapes and sites taxonomically by the number of elements represented into the two main groups of natural and cultural landscapes, and then to subdivide the first group further according to the degree of integration, i.e., according to the number of spheres represented.

The intra-functional relationships will be measured according to their intensity, though I would not yet be prepared to give you a scale for such a measurement. At the moment we could only make qualitative statements.

Factors such as the steering mechanism deserve special attention. While the whole system always tends to achieve a certain state of balance, which it will attain if no factoral changes occur and enough time is allowed to reach that climax stage, any factoral change will create unbalance within the system and a chain reaction of changes of various elements ensues.

The major advantage of such a model of the geospheric system at the present time is probably that we always consider the geospheric whole at a given

site and that we do not lose sight of what may happen in neighbouring fields. With respect to our immediate problem, it means: (a) that first of all we have to know the anthropogenic or human factor well enough to evaluate its influence and that we have to carry out anthropological and sociological studies as carefully as those in pure natural science; (b) that following this we will set our model into motion by certain changes produced by the action of man. Even if we are to report primarily on the changes that can be observed in soils and vegetation as a result of such an action, we shall never lose sight of the fact that these two elements are correlated with all the others present in the system although by a varying intensity of correlation.

I am fully aware of the fact that these are very general remarks, and that in this century of rapidly increasing specialization in every field the work of the specialists becomes more and more important and indispensable for the advancement of our knowledge. However, the more specialization takes place, the more necessary it becomes to have a solid general framework into which the results of the individual researchers can be fitted. A model such as the one with which the geographers work is even more important because it prevents us from forgetting that the world with which we are concerned is to be considered as a whole.

Résumé

L'influence des activités traditionnelles de l'homme sur le sol et la végétation (H. Boesch)

Dans cet exposé deux aspects du problème sont discutés :

1. L'influence directe de l'homme sur la morphologie, le sol et la végétation. Une publication du Département de géographie de l'Université de Dacca, *Land-use in Rampal Area* (Monograph I, 1961), y est particulièrement citée, laquelle contient des exemples détaillés de la façon dont l'homme a changé la géomorphologie locale pour maîtriser les inondations annuelles. Ainsi l'homme a obtenu — par terrassement — des conditions identiques pour la formation du sol et la protection contre les nondations; il a par conséquent gagné des terres à cultiver assez étendues. Même si ces changements semblent être très modestes — certains sont presque invisibles à première vue dans les champs — ils ont une influence considérable sur les possibilités de vie dans ces régions menacées par les inondations. Toutefois les activités traditionnelles de l'homme ont à peine changé la morphologie ou le sol. Quant à la végétation, aucune information n'existe en ce qui concerne la flore naturelle d'autrefois.

2. Suit un exposé de certains aspects méthodologiques de la recherche en géographie. L'auteur fait ressortir l'importance d'un concept modèle pour atteindre une meilleure clarté d'ensemble et la possibilité de traiter ces problèmes selon des principes mathématiques.

Discussion

J. Reksohadiprodjo. Professor Boesch maintains that it is not possible to define natural vegetation exactly. But could we not say that in humid tropical regions the natural vegetation consists of the tropical rain forest, in which man may intrude when gathering forest produce and afterwards by applying shifting cultivation systems?

D. Mueller-Dombois. It appears very important to view deltas as ecosystems and to emphasize the factors that interact within their boundaries, because land management will then be led to consider all aspects of land use. When this is recognized, landscape surgery will be restricted to mere modifications in order to improve upon nature within its own framework. Moreover, delta ecosystems cannot be understood as isolated units since they are constantly influenced by forces originating outside their boundaries. For example, it seems obvious that delta formation and sedimentation are closely correlated with conditions in the catchment area. It would be interesting to pay particular attention to the changing conditions (e.g., forest management) in catchment areas in an attempt to study and compare delta formations as natural or unnatural processes. Answers to important management problems could probably be obtained from such studies.

H. T. Verstappen. Evaluation of natural environment and natural resources are actually cultural appraisals. Prior to the introduction of wet rice cultivation, irrigation largely missed deltaic areas and preferably existed in the upland areas, not subject to flooding. Man's influence in the deltas of South-East Asia started only after irrigation techniques were mastered. From then on, these deltas were gradually appreciated as a favourable addition to the environment. In earlier days they were considered unfavourably.

A. Wirthmann. I should only like to point out that in all south-eastern Asia, the wet cultivation of timbers (*taro*) on the coast preceeded by many centuries wet rice cultivation. These floodplains and deltaic areas might have been settled gradually before the introduction of irrigated rice.

Agriculture with special reference to rice cultivation in humid tropical zone deltas

G. A. W. van de Goor

INTRODUCTION

The humid tropical zone deltas are comparatively densely populated. A large population can be supported in these deltas because of the combination of climatological, hydrological (agrohydrological) and soil conditions which have made continuous rice cultivation possible at a moderately high level of production without the necessity for long fallow periods.

It is not so much the climate as the hydrology and the type of soil in the deltaic areas which distinguish these areas from other parts of the river. The principal distinguishing features are: the annually occurring floods, the influence of the tides and salinity problems, the sedimentation of fine soil matter resulting in heavy clay soils, the local occurrence of potentially acid clays, the development of organic soils, the general low elevation of the land which implies a high groundwater table especially during the wet monsoon, the slight inclination of the land.

The first two factors generally imply—though on a primitive scale—human interference with the movement of water in the delta.

The high clay content of the soils provides a fairly high level of fertility but makes them physically difficult to handle.

Unripe (azonal) soils—saline soils, potentially acid soils and organic soils—all have their specific problems requiring special treatment. The low elevation and the slight inclination of the land make it extremely difficult to drain any surface and internal water which is excessive for agricultural purposes from the soil.

Development and/or maintenance of soil structure—a condition of the soil important for crop production—is difficult in wet soils and under conditions of high rainfall.

Deterioration of structure is enhanced in saline soils with high sodium and magnesium contents.

The wet conditions generally favour an abundant growth of marsh vegetation, which will compete with the crop plants and even choke growth completely if the crop does not possess characteristics which encourage survival and will enable it to grow at a more rapid rate than such weed plants.

The plant which not only can cope with these adverse conditions but even profits and benefits from them is rice, especially if man assists.

Human intervention consists in choosing the variety which possesses the necessary characteristics to survive and to grow under the prevailing hydrological conditions or in changing these conditions to some extent and in applying those cultivation techniques which reduce as much as possible any factors detrimental to crop growth.

Thus, different kinds of rice cultivation have developed which provide the best results under the natural conditions or after simple changes to the hydrology of the area.

This paper will deal with agriculture, and more specifically rice cultivation, in the deltaic areas. It will describe the specific characteristics of rice cultivation and the most important possibilities for its adaptation to conditions in hydrologically different parts of the delta.

Special reference will be made to the deltaic areas in the humid tropical zone (Anon., 1963). With regard to the improvement of agricultural conditions, examples will be taken from the Nobi delta in Japan and the Cho-Shui delta in Taiwan where various technical measures make a more efficient water control possible. Better water control is a condition *sine qua non* for an effective improvement of agriculture in the deltaic areas. In comparing these other areas with the tropical humid zone deltas it should be remembered that climatic conditions here differ from those in Japan and Taiwan.

GENERAL INFORMATION ON HUMID TROPICAL ZONE DELTAS

The climate in the humid tropical zone deltas of South-East Asia is characterized by high rainfall during the wet monsoon, which lasts six to seven months (from

April/May to September/October), varying from 1,187 mm. (Bangkok) to 2,695 mm. (Rangoon). Rainfall during the other five or six months of the year amounts to only 114-200 mm. The average temperature during the wet season is high and constant (28° to 29° C.) and lower during the dry season, ranging from 23.5° C. (Calcutta) to about 27° C. (Bangkok, Rangoon).

The rainfall pattern in Taiwan is similar, but the average temperature during the winter is lower (19.1° C.). In Japan, there is high rainfall throughout the year, temperatures on the whole being lower and very low during the winter. The soils are chiefly sediments from erosion matter transported by the rivers from higher areas. These alluvial soils are mainly clays to very heavy clays. In deeper parts of the delta organic soils are formed. River levees and sandy ridges—present and former beach lines—are above the average level of the alluvial plain and suited for human occupation, as they provide a safeguard against floods. The deltaic alluvial plains are generally flat with a slight inclination which levels out on nearing the coast.

The rivers cause occasional floods during the wet season which inundate the deltaic and lower river areas for shorter or longer periods. These high floods often coincide with high rainfall in the delta. Hydrologically, therefore (as has also been mentioned in other papers) an area is distinguished starting from the apex to the lower part of the delta which is principally affected by the river flood. Near the coast, a zone in the deltaic area is subject to tidal flooding. Here along the beach lines a mangrove vegetation has generally developed. In between these two zones an intermediate zone is found which is affected by river or sea floods. The extent of river or sea influence varies according to the time of the year.

These three zones possess their own specific problems with regard to agricultural possibilities.

Man adapted himself to the natural conditions not only choosing the higher parts of the delta for habitation but also by selecting a crop and methods of cultivation for the low parts during the rainy season.

The relatively fertile soil conditions in the delta and the abundant supply of water and silt and plant nutrients created comparatively favourable conditions for a livelihood based on sedentary agriculture in a climate which generally gives rise to poor, leached soils and, in other respects, only permits a kind of shifting cultivation or more or less forest-type crops (Pendleton, 1950).

In the case of wet rice cultivation this is different. Rice is a crop that can be grown year after year without interruption. Yields remain at fairly good levels.[1] Continually good yields are impossible with dry cultivated crops, not only in the humid tropics, but also in other climatic zones. In these cases moderate yield levels could be obtained for the years in which a crop could be grown only either by shifting cultivation or by inserting a fallow period.

Moreover, the specific characteristics of rice cultivation make it suited not only for flooded and waterlogged soils, but also for saline soils, organic (peat) soils and cat-clays. All such soils are of common occurrence in deltaic areas.

In the different deltas, the agrarian structure is characterized by family farms. The average size of the farm per family varies from 1.5 hectares in the Sunderbans delta to about 3-5 hectares in the Chao-Phya and Irrawaddy deltas. The size of the holdings in the Nobi and Cho-Shui deltas is even smaller.

Although the size of the farms is already small in the various deltas, parcelling and subdivision of the farmland makes conditions even worse.

Parcels of the largest size and the lowest number of parcels per farm are found in the Chao-Phya delta and here the holdings are also the biggest. Bad parcelling has great disadvantages when mechanization has to be introduced.

In the tropical deltas and also in the Cho-Shui delta most of the population is engaged in agriculture, which as we have stated, is the main source of livelihood.

With only one rice crop in the tropical deltas, there is much unemployment.

In the Nobi and Cho-Shui deltas good road systems connect agricultural areas with villages and towns. Internal communications within the farm units are rapidly being improved there.

In the other deltas, rivers and canals provide almost the only means of communication.

Access to the parcels is obtained by walking along the field bunds. Only in part of the Nobi delta are farm houses connected to a public water supply system. In the other parts of the delta, ground water is used.

In the other deltas, the common sources of water supply are rain water (tanks), ground water (wells, pumps), river and canal water, pond water and central water supply stations.

Electricity is not available in the humid tropical zone deltas. Paraffin lamps are used.

Mechanization in these tropical deltas is in its primitive stage.

Man has, moreover, achieved a fairly high standard of health. There is, generally speaking, little malaria in comparison with the adjacent higher areas, owing to the introduction and practice of wet rice cultivation (Gourou, 1958; Ooi, 1959). The disappearance of malaria in large parts of the delta is, next to the relatively favourable physical conditions for paddy production, the reason for the dense population in the areas. Rice cultivation was therefore the key which opened the

1. This advantage of lowland rice cultivation in the relatively fertile tropical alluvial deltas and river plains is not so important now and is less of an exception, since with the application of fertilizers and other modifications constantly good yields of other crops can also be obtained from the same piece of land under totally different conditions.

deltas for permanent human occupation in humid tropical zones.

AGRICULTURE

General remarks

Agriculture is the principal source of livelihood in the different deltas. Only in the Nobi delta (Japan) is industry becoming increasingly important. Rice is the only crop naturally adapted to the climatological, hydrological and edaphic conditions prevailing in the humid tropical zone deltas. The main rice season in all deltas is during the wet monsoon which ranges from April/May until September/October. In the tropical deltas, viz. Chao-Phya, Irrawaddy, Mekong and the Sunderbans, single rice cropping during the main season is predominant. Owing to lack of rainfall and the heavy characteristics of the soil, it is difficult, if not impossible, to grow a second crop in the dry season without irrigation facilities and without adequate soil tillage implements or even better mechanization.

Multiple cropping is, therefore, only practised in the Nobi delta and in the Cho-Shui delta in Taiwan. In Japan, wheat, barley or rape seed are grown during the winter when temperatures are far too low for rice.

In the Cho-Shui delta, double cropping with rice is becoming a common practice. Both *Japonica* (Ponlai) and *Indica* (Chailai) varieties are planted. A three-year rotation is also practised to some extent, in which rice is alternated with sugar-cane, green manure, sweet potatoes, peanuts, soya beans, etc.

General characteristics of rice cultivation

Dry rice or upland rice is not cultivated in the deltas. The discussion of the characteristics and problems of rice cultivation will therefore be restricted to wet rice or lowland rice.

Lowland rice is grown in fields which are covered with a layer of water during the greater part of the growth and development of the rice plants. The length of the growing period depends on the variety, the choice of which is, generally, based on the agrohydrologic conditions in the rainy season. The almost constant temperatures and the amount of daylight have less or no influence on the choice of variety.

The water régime of the rice fields and its influence

The depth of the layer of water for the type of rice normally grown varies from 5 to 15 cm., but, in flat areas, it is often much more and seldom less. An average depth of about 10 cm. is favoured. This depth, on the one hand, does not hinder the tillage of the rice plants, and hence the production, too much; on the other hand, in most instances the depth of water is sufficient to control the growth of harmful weed plants. High rainfall and floods during the wet season may both give rise to wet and flooded fields, conditions which are not suited to the growth of most annual food crops. The same conditions, however, have proved to be favourable for rice production. The excessive supply of water prohibitive for the growth of most crops made conditions for rice such that it could be grown over an indefinite number of years without too much risk of crop failure, without too great a fluctuation in yield and without any marked signs of exhaustion of soil fertility or deterioration of soil structure.

Man generally tried by various means to exert an influence both on the depth of flooding and on the length of flooding period most suited to the kind of rice to be grown. Thus, he obtained under the prevailing conditions and with the means at his disposal more security for crop growth and higher yields. In order to control the length and depth of flooding it was often necessary to interfere with the natural course of the flood and rain water. A certain kind of terracing by making field bunds on the contours and the provision of simple irrigation and drainage facilities were necessary. The effect of this human interference with nature is favourable for rice production in many respects. Erosion is less severe because the field bunds check the rate of flow of run-off water and because the force of the rainfall is broken by the water layer present on rice fields throughout the wet season. On the other hand, sedimentation of silt in the fields between the bunds will be promoted. The fertility of the soil is for the same reason not easily exhausted, because most of the nutritional requirements of the rice plant are supplied either directly by the irrigation water or indirectly by the silt carried in the water.

Loss of nutrients by leaching does not occur or, if so, only to a lesser degree, because in lowland rice fields vertical movement of water through the soil is prevented in order that the layer of water on the fields is maintained. Various practices are, therefore, employed to control the percolation. Depending on such circumstances as topography and types of soil, this may be attained in deltaic areas either by utilizing certain soil tillage practices which result in the establishment of a more or less impervious soil layer or by keeping soil-water tables above field level by maintaining high water levels in canals and channels. The hydrology of rice fields differs, therefore, in many respects from that of fields under natural conditions. Vertical movement of water will decrease, whereas, simultaneously, water storage on the fields will increase.

Waterlogging, or even stagnancy and a lower redox potential under more or less severe reduction conditions, will be the result. Plants like rice, which belongs to the category of emergent, anchored hydrophytes, are adapted to environments which are unfavourable for most other plants, provided that reduction does not become too extreme.

The consequences of such circumstances are: less

oxygen present in the soil, superabundance of water, reduction of oxides such as ferric and manganic oxides to ferrous and manganous oxides, denitrification of nitrates and increase of ammonification, increase in the availability of phosphates, increase of pH, anaerobic decomposition of organic matter resulting not only in the production of ammonia but also in various noxious products such as carbon dioxide, methane, hydrogen sulphide, buturic acid and other organic acids (Basak and Bhattacharya, 1962; Harrison and Aiyer, 1913; Jeffery, 1963; Mitsui, 1954; Ponnamperuma, 1955).

Moreover, the presence of the layer of water promotes the growth of rice, prevents the growth of weeds and encourages the development of blue-green algae (Cyanophyceae) in the interface soil/water (De and Sulaiman, 1950; Harada, 1954). These organisms are capable of fixing nitrogen from the atmosphere. Since they are autotrophic as a result of the process of photosynthesis, it follows that nitrogen fixation is, in this case, independent of any external supply of oxidizable matter. Simultaneously, the oxygen released during photosynthesis aerates the surface layer of the soil to a depth of about 1 to 2 cm. This thin oxidized layer above a more or less heavily reduced layer is not only important for the development of the aerobic part of the rice root system (especially in the final growth phases of the plant), but also for other aerobic processes.

Weed growth, which is usually very troublesome and even prohibitive for agriculture in the lower deltaic plains is effectively controlled for a large number of reasons (van der Goor, 1955). The possibility of varying the height of the water layer, especially during the first phase of growth after transplanting, is one of the more important means of checking the growth of weed plants. Other means of weed control inherent in rice cultivation are: the raising of seedlings in small nurseries so that they need less tending; the careful selection of seedlings when being transplanted to avoid their contamination with weed plants; the levelling of fields before transplanting, as a result of which weeds are destroyed; the removal of any remaining weed plants during transplanting; the fact that rice seedlings transplanted in the field are well ahead of newly developing weed plants; the fact that, as the composition of weed vegetation will be completely different during what is often an extremely dry season, a gradual increase of weed plants is prevented by this regular interruption.

Rice diseases and pests may also be adapted to the flooded conditions of these fields. If temporary drainage of the fields is possible, this is a very effective means of controlling some of the more severe diseases and pests (Logothetis and Ling, 1951).

Since the larvae of malaria mosquitoes and the vectors of bilharzia prefer oxygenated water, the contamination of the water with heavy weed growth cut to prepare the rice-fields will prevent the growth of these vectors because oxygen is withdrawn from the milieu as a result of the decomposition of organic matter. Furthermore, the fact that the motion of the water in the deltas is relatively slow because of the slightness of the inclination and that this motion is further impeded by the field bunds makes the water less favourable for the breeding of the larvae of the *Anopheles* species than, for instance, the water in the adjacent higher lands (Gourou, 1958, Ooi, 1959).

It will be evident from the characteristics inherent in rice cultivation that it became the type of cultivation *par excellence* for humid tropical zones.

The intrinsic fertility of the deltaic soils with a higher clay content, the absence of the degradation which is a normal process in soils in the adjacent areas and the abundant water supply in the deltas make them potentially very favourable areas.

Other types of agriculture

Flooding, high water tables (especially in the wet season) and the inadequate drainage facilities in the deltaic lowlands make it difficult to grow other crops.

Coconuts are grown on higher sites in the deltas, on village land or river levees and sandy ridges near the coast. There may be ground water within the root range of such trees, the roots "touching" the water, but the ebb and flow of the tides prevent the water from becoming stagnant.

Other perennials like the oil palm may be grown, provided that there are adequate drainage facilities.

The lack of rainfall in the dry season and the hard soil are two factors which do not promote the proper tillage of the soil and the germination and first growth of seedlings of annual crops. Annual crops can therefore only be grown during the dry season when there is still sufficient rainfall to soften the soil and thus make tillage of the soil and germination of seeds possible.

Irrigation facilities during the off-season are generally limited and only permit the growth of vegetables on small parts of the area, as is the case in the Bangkok area. In the subtropical areas it is possible to grow winter crops like barley (Japan, Nobi delta).

The possible growth of "dry" cultivated crops in the dry season may favour the drying and aeration of the rice soils (van de Goor and Zijlstra, 1963).

Double rice cropping is practised to some extent in the Cho-Shui delta. Water buffaloes and other cattle, which are present in various deltas, obtain food from wild growth in the wet season and from the paddy stubble, second shooting and weed growth which develops on the residual moisture after the harvest of the rice.

Different types of rice cultivation adapted to different hydrological conditions

Rice is grown under different soil moisture content conditions varying from those where the available

moisture is below the field capacity of the soil to those where the soils are completely flooded. Varieties of ice are fround which differ according to the amount and distribution of rainfall, the increasing and decreasing inundations of the land and the saline, acid or reduced condition of the soils.

Rain-dependent dry-land rice or upland rice is only grown on the higher lands adjacent to the deltaic area. This type of rice, which is grown in the same way as other dry-land crops although not belonging to the category of delta agriculture, demonstrates the wide range of adaptability of rice with regard to soil moisture conditions and water supply.

Floating rice (*riz flottant*) is found at the other end of the range of adaptability to water conditions. This type of rice, sown early enough to be well established before the floods gradually start to inundate the land, possesses the capacity of rapid growth (5 to 15 cm. per day) and thus keeps pace with the rise of the flood water. The total height attained is from 3 to 5 metres (Coyaud, 1950).

Floating rice is generally found in the more upstream regions of the various deltas, e.g., where lands are inundated from the end of June to the end of September or beginning of October. The depth of inundation varies from 1 to 5 metres. At the end of the dry season, grasses and other vegetation are burned. After the first rains in April, the land is ploughed and harrowed. The seed is broadcast when the soil is sufficiently moist. The seed should be sown about two months prior to the start of flooding in order to ensure that the plants are well established. Their shoots should have attained heights of 50 to 90 cm. when the water in the fields gradually starts to rise. Harvesting is done either when the soils are dry or when there still is water in the fields at the end of November and December.

Yields are about 700 to 1,000 kg. per hectare but may be much higher under favourable conditions.

Once every five to seven years there is a total failure. Factors influencing the success of floating rice are the time of sowing, the growth of weed plants, the rate of rise of water, the velocity of the winds and the activities of birds and crabs (de Vries, 1961).

In the case of floating rice, no special efforts are made to control the water. Sometimes wind-breaks consisting of leguminous plants like *Sesbania paludosa* are grown to prevent damage by waves.

Deep-water rice (*riz demi-flottant* and *riz haute tige*) is grown in areas where inundation is considerably less. The maximum depth of inundation which can be tolerated is about 1.5 metres. This type of rice is transplanted (Coyaud, 1950).

In areas where the rate of the rise of the water or the total depth of inundation is too great rice is grown during the off-season. This is sometimes known as marsh rice (*riz de décrue*). Seeds are sown during the wet season either on higher ground in the area or in floating nurseries. When the water in the fields is low enough, the seedlings are transplanted and field bunds are erected to keep the remaining water in the fields (Coyaud, 1950).

Areas where double transplanting is practised are found, for instance, in the Mekong area downstream of the floating rice area. Rice fields are subject to an average inundation of 40 to 60 cm. to a maximum of 100 cm. during the months of September and October. Because of the abundant weed vegetation and the high organic matter content of the soil (superabundant nitrogen supply) and the topography of the area, double transplanting (*rizières à deux repiquages*) proved to give the best results. The type of rice cultivation which is found over the largest area in all lowlands (deltas included) is the traditional method of lowland rice cultivation which may be either completely rain-dependent or irrigated. The depth of water in the field and the length of the irrigation period are generally controlled to some degree. The fields are generally well prepared and supplied with bunds which follow the contour. Transplanting or seeding in the field is practised (Coyaud, 1950).

Although many variations may be encountered in the different deltaic lowlands, the above-mentioned types of rice cultivation are the general types from which the other variations may be derived.

Rice cultivation on different types of soil

Rice cultivation, which is so tolerant of so many different types of water conditions, is also tolerant of adverse chemical soil conditions.

In the deltas, e.g., in the Sunderbans, large areas are inundated by sea-water. They will gradually be protected against the protrusion of this sea-water. The salts are leached out with the water used to cultivate and irrigate the rice fields. Rice seedlings are raised on less saline nurseries. Saline-resistant varieties are used during the first years of reclamation. The ability of rice to grow in saline soil may be related to management practices employed (Jordan, 1963; Pearson, 1961). Soils carrying large amounts of sulphides occur frequently in coastal tidal mangrove swamps. When such soils are aerated as a result of good drainage conditions, cat-clays are formed which are harmful because of high aluminium ion concentrations and extremely high acidity. The best way to prevent aeration is, therefore, to grow one or, even better, two rice crops per year. This practice will keep the soil under water for the greater part of the year and prevent pyrite oxidation. The harmful products which might be formed during the relatively short aeration period will be flushed and leached away with the irrigation water. In Japan, lime is added to the soil. In Sierra Leone (Anon., 1960; Hart *et al.*, 1963) and Viet-Nam, the first flushing is done with sea-water to economize on the use of the irrigation water. Moreover, the fact

that rice is rather tolerant towards the toxic compounds formed means that its cultivation is very well adapted to such circumstances. Rice is also grown on organic soils, provided that the layer of peat is not too thick (not more than about 20 to 30 cm.). It is, however, advisable in these cases, if conditions allow, to start during the first years of reclamation with the cultivation of dry crops such as chillies, colocasia, pineapple, vegetables, etc.

It may be concluded that, under the natural conditions of the delta after only slight improvements to the hydrology of the fields, rice culture is possible under a wide variety of soil and water conditions.

WATER CONTROL FOR AGRICULTURAL PURPOSES

General remarks

Proper water control is only possible if the water requirements of the various crops to be grown are sufficiently recognized. Rice is and will remain the principal crop in the deltas. Other crops may, however, be rotated with rice during the dry season. A study of the existing types of rice cultivation adapted to the hydrological conditions in the deltas revealed that, with or without only slight modifications, continuous production had been obtained for centuries. The yields vary from about 500-700 kg. per hectare for floating rice to 2,000 kg. per hectare for common lowland rice in the Chao-Phya and Irrawaddy deltas. It is, however, evident that these yields are low and could be considerably increased, as has happened in the Nobi (6,500 kg. per hectare) and the Cho-Shui (5,000 kg. per hectare) deltas. To achieve this, the factors responsible for these rather low yields should be changed. The various and often interrelated factors are as follows: inadequate agrohydrological conditions, physically and chemically difficult soils. The social and economic factors do not differ greatly from those in areas adjacent to the deltas.

In order to improve the agrohydrological conditions, it is necessary to study the water requirements for rice and other crops.

The requirements for rice will, however, mainly dictate what steps have to be taken to improve agrohydrological conditions.

Net use of water

The net use of water (van de Goor and Zijlstra, 1963) during the growth of rice in the fields consists of evapotranspiration, i.e., transpiration of water by the plants plus direct evaporation from the immediate environment, and percolation of the water to the subsoil. Seepage may be disregarded in the case of large areas.

This net water use can be determined from a study of the water balance. To do this, it is necessary to select an area which can be isolated hydrologically from the surrounding area without making it thereby non-representative. This is possible in a pilot area. The water supplied to the area by rainfall (R) and/or irrigation (I) as well as the surface run-off (S) must be measured. The net water use (CU) can then be determined from the formula $CU = R + I - S$.

Evapotranspiration

The process of evapotranspiration (van de Goor and Zijlstra, 1963) is governed largely by the climatic conditions which are responsible for the energy available for evaporation. The relationship with climatological data can therefore be used to calculate evapotranspiration.

Various methods of calculation have been presented by Penman, Blaney-Criddle, etc. In flooded rice fields evapotranspiration will never be restricted by the lack of soil moisture and, if other environmental conditions are favourable, will always be at the maximum rate possible under the climatic conditions, i.e., that of potential evapotranspiration. This will have a favourable influence on photosynthesis and net assimilation. Since in the tropical zone the total solar radiation does not vary greatly, evapotranspiration in the rice field will be more or less constant throughout the growth of the rice plant. Slight variations may be caused by the influence of cloudiness and the humidity of the air and wind. Immediately after sowing or transplanting, the evapotranspiration will consist mainly of evapotranspiration of the water surface, but the rate of transpiration of the plant will soon increase. It is found that around the reproductive phase of the rice plant evapotranspiration (chiefly transpiration) is higher than that calculated from climatological data (van de Goor, 1950). This seems to indicate that the phase of the plant's development should also be considered when these physical data are being used. Evapotranspiration in rice fields can be determined in lysimeters placed in the actual field. Rice is planted and irrigated in these lysimeters in exactly the same way as in the fields.

The presence of the water layer at the same level on the soil in the lysimeter as in the field prevents the occurrence of temperature differences. The evapotranspiration thus determined will, therefore, correspond to that in the rice fields.

The evapotranspiration value for the tropical humid zone deltas varies from 4 to 6 mm. per day. Occasionally during flowering it may attain values of 7 to 8 mm. but this will not have any substantial influence on the water supply of rice fields.

Percolation

As free water is kept on the rice fields for the greater part of the growing period, water loss might occur as a result of the percolation of water to the subsoil to a natural or artificial drainage channel (van de Goor

and Zijlstra, 1963). The magnitude of this percolation loss naturally depends on the permeability of the soil layers (an impermeable layer in the profiles could reduce percolation completely), the relative water levels in the field and in the drain, and the distance to the drain.

The possible percolation (P) of water to the subsoil may be found from the formula: $P = CU - ET$.

The pilot areas should be large enough to allow for accurate measurement of water entering and leaving the field.

Not only values for the net use of water but also estimates of the percentage of effective rainfall can be obtained. In most of the deltaic areas in South-East Asia the total amount of precipitation during the growing season is nearly sufficient for one crop per year, but only a portion of this rain is effective because of its irregular distribution.

It is often observed that there is a shortage of rainfall during certain periods in the rice season, so that supplementary irrigation will be necessary. As already stated, it is expected that, on the heavy soils in the deltas, percolation will be small, because of either the kind of irrigation or the kind of tillage of the soil to be practised. The irrigation applied in flat areas often consists of a kind of "controlled inundation" and the water levels in the irrigation canals, on the field and in the drain channels are kept at approximately the same average level. Under these circumstances, percolation is effectively reduced to a negligible amount.

In other cases, prevention of percolation may be effected by tillage of the soil. Forms of tillage such as ploughing, harrowing, etc., are performed under flooded conditions to prevent weed growth, to enable the old rice stubble to be incorporated in the soil and to prepare the soft muddy conditions which favour the growth of rice. At the same time a degree of soil levelling is achieved. As a result of this wet soil tillage a more or less impermeable layer is established without complete puddling of the soil. Hence, percolation losses will be reduced considerably. Although losses by percolation should be prevented, some percolation may sometimes be desirable.

This may be the case for saline soils, acid clays and heavily reduced soils, for which percolation to a certain degree will be helpful both for the removal of toxic compounds by leaching and for the creation of an oxygen supply.

Presaturation

Before rice is sown or transplanted on the field, water is necessary for the saturation of the soil and to establish a water layer in the field (van de Goor and Zijlstra, 1963).

During this period—which varies from two to eight weeks (the presaturation period)—the soil is tilled. Depending on the type of soil, a certain amount of water will be needed to saturate it and to achieve the required muddy conditions. It is estimated that for these deltaic soils, 100 to 200 mm. (4 to 8 inches) are required.

A layer of 150 mm. of water above the soil level should be deep enough to control the growth of weeds and yet be not too deep to check the tillage and growth of rice.

More information is required with regard to the optimum height of the water during the various phases of growth and with regard to the optimum depth and time of inundation (plants partly or completely submerged) which can be tolerated by the rice plants.

The water required during the presaturation period to saturate the soil and to establish and maintain the layer of water can be expressed mathematically as follows (van de Goor and Zijlstra, 1963):

$$cAdt = aydt + bdy$$

in which

c = supply required during presaturation period, expressed as inch/day over total irrigable area A,
A = total irrigable area in scheme,
t = time (days),
a = supply required during normal irrigation period after presaturation is completed (inch/day),
y = area presaturated at time t,
b = water required for presaturation (inches).

The development of the above formula gives:

$$c = a \frac{e^{\frac{aT}{b}}}{e^{\frac{aT}{b}} - 1}.$$

As is found in practice, the water requirements are about 50 per cent higher during the presaturation soil tillage (and nursery) period than during the rice-growing period.

Drainage

Little is known about the drainage requirements for rice. When extreme reduction occurs, which may be the case prior to the reproductive phase of rice, drainage of the land may improve the situation (van de Goor and Zijlstra, 1963). This practice is known as mid-drying (Matsuo, 1961; Matsushima, 1963).

Soils rich in organic matter and/or low in iron compounds are especially liable to become severely reduced.

Water levels higher than about 15-20 cm. in the field should be avoided during the greater part of the growth of the rice as they do not favour optimum production.

From the information with regard to rice cultivation it will be possible to determine for the various phases the daily water requirements in the different parts of the delta and what water levels may be tolerated in the wet season.

Rice fields can be used temporarily to store excess water over and above that in the drainage system itself. The total depth of water to be tolerated in the

fields may be different according to the phase of growth and the length of the inundation period. Total submergence of the plants for longer than a few days, especially during the reproductive phase, should be avoided. Submergence during the ripening of the crop may increase lodging and be detrimental to the quality of the seed. Storage of water on the paddy fields helps to decrease the costs of the drainage system. Only in certain cases may drainage of rice fields be required to remove toxic compounds. During the maturation of the rice, drainage of water from the fields is necessary. A more intensive system of drainage is sometimes practised, as for instance, on the Nile delta and the Cho-Shui delta (intermittent irrigation) (Lee and Chow, 1958). High yields are claimed under these conditions. Problems with regard to weeds may, however, arise. If the fields are also to be used for dry-cultivated crops, a more intensive drainage system is essential, e.g., separate irrigation and drainage canals and channels for adequate water control. On the generally heavy clay soils of deltaic areas, deep drainage may be needed, in which case tile drains may sometimes be useful.

Water requirements for other crops

Other crops require water chiefly for evapotranspiration. If it is assumed that the evapotranspiration for crops other than rice is about 75 per cent of the potential evaporation and distribution losses are only 25 per cent (as compared with 50 per cent in the case of rice), then the irrigation duty will be about 150 mm. per month. Moreover, rainfall is often quite effective in satisfying the water requirements of dry-land crops.

For the cultivation of dry-land crops, more intensive and deeper drainage is often required for good root development and a higher water storage capacity of the soil. In all deltas, irrigation is, however, concentrated on the rice crop and not on crops to be grown during the dry season. This is even true of the Nobi and Cho-Shui deltas.

Distribution of irrigation water in the fields

For a more economic use of the available water, the methods of rotational irrigation and intermittent irrigation practised in the Cho-Shui delta deserve attention.

For the proper use and control of water, irrigation areas should be subdivided into smaller units, each equipped with measuring devices. The selection of units should be based on topographical conditions and hence on irrigation and drainage facilities.

Such individual irrigation units within a larger irrigation area should be provided internally with an adequate system of distributary and field channels suited to the topography of that particular block. Only in such a way will it be possible for water to reach all the fields in good time, so that the lower lying fields are not inundated for too long a time, as is now frequently the case.

The drainage facilities of such units should be adapted to the requirements of the crops to be grown.

LAND USE AND CROPPING PATTERN

In the deltas of the humid tropical zone because of the rainfall distribution and the hydrology of river, sea and land, only one crop of rice is grown during the wet season (main season). Conditions for other annual crops are on the whole unfavourable during this season. During the dry season (off-season) soil and moisture conditions are naturally not very well suited to the cultivation of crops. With a better knowledge of the irrigation and drainage requirements for rice and other crops throughout the year, improved water control in the deltaic area will open the way to multiple cropping and more intensive and productive farming.

The possibility of double cropping with rice crops or with rice and other crops, together with any other factors which may increase production, will be considered.

For double cropping with rice, more water will be needed than when rice is grown only in the wet season and no rice or other crop is grown in the dry season.

Rice is an exceptional crop, in that it can be grown year after year on the same land without any decline in yield, as is the case with most other crops grown in monoculture. However, when two rice crops per year are grown on the same land, a completely different situation develops. Under a system of one rice crop per year there is always a long off-season during which the soil is not irrigated. During this period, regeneration of the soil takes place, which brings the soil back into a suitable condition for the next main-season rice crop. This regeneration consists mainly of the oxidation of harmful reduced substances, formed under the waterlogged soil conditions during the growing of the previous rice crop. The greater the development of harmful substances during the rice-growing period the more necessary this regeneration is. The harmful substances are mainly reduced organic products formed under the anaerobic conditions which exist in the flooded rice field.

The more organic matter there is in the soil and the more fresh weed growth is added to the flooded rice field, the greater is the chance that harmful reduced products will develop. A longer rice-growing period will also increase the accumulation of reduced substances.

Peat and muck soils and soils which support a heavy growth of water weeds in the off-season, are, because of their high content of easily decomposable organic matter very liable to excessive reduced conditions. These soils, because of their low situation usually experience aeration and regeneration difficulties in the off-season.

Moreover, under the system of one rice crop per year with a long off-season, the diseases and pests associated with rice are naturally drastically reduced because of the lack of host plants and because of completely diffe-

rent soil conditions. By introducing a second rice crop in the same year, the possibilities of aeration and regeneration decrease, whereas those of reduction increase. The incidence of diseases, pests and weeds is also increased under such circumstances.

In a double cropping system it is important that presaturation should not take too long. If presaturation is extended over too long a period there will be less time available either for the drying and aeration of the soil or for the growth of rice after transplanting. In both cases decreased production may be expected. On the other hand, a very short presaturation period will mean that intensive irrigation is required only during this short period.

The system of growing other crops than rice in the rice off-season will, however, have a favourable influence on the production of the succeeding main-season rice crop. The following factors contribute to this favourable effect. For these crops the soil is tilled intensively under "dry" conditions. The organic matter is mixed thoroughly throughout the soil and is decomposed aerobically, so that a more stable form of organic matter arises which combines with the clay and is not so liable to reduction. The result is a friable top soil which promotes food root development. The good aeration of the soil which results from the intensive tillage, together with the extraction of water from the soil by the plant roots, very effectively removes the harmful reduced substances which arose during the preceding rice period.

The chances of the development of weeds under such an intensive system of cultivation are very slight. Soil preparation for the succeeding rice crop can be very simple, since the soil has already been thoroughly tilled and there is no weed growth to be removed. As soon as the irrigation water has reached the fields, the rice seedlings can be transplanted.

Under this system of agriculture, as we have just stated above, the chances of the development of large quantities of harmful reduced substances in the paddy soil are much slighter, and these harmful substances are much more effectively removed during the off-season. Consequently, both the main-season rice and the off-season crops can be expected to have high yields.

The principal crops worth trying (van de Goor, 1955) are:

Various legumes grown for seed: *Arachis hypogaea* (ground nuts), *Glycine max* (soya beans), *Phaseolus lunatus* (lima beans), *Ph. radiatus*, *Ph. mungo* (black gram), *Ph. rheus* (green gram), *Ph. calcaratus* (rice beans), *Cicer arietinum* (gram, chick pea), *Lathyrus sativum* (khesari), *Vigna sinensis* (cow peas), *V. katjang*, *Dolichos lablab*, *Cyamopsis tetragonolobus* (gua), *Canavalia ensiformis*, *Cajanus cajan* (red gram), *C. indicus* (pigeon pea).

Leguminous plants for soil improvement and green manure purposes: *Crotalaria juncea*, *C. anagyroides*, *C. usaramoensis*, *Sesbania speciosa*, *S. sericea*, *S. aculeata*, *Cassia tora*, *C. leschenaultiana*, *Stizolobium deeringianum*.

Cereal crops: maize, millets (*Pennisetum*, *Panicum*, *Setaria*, *Eleusine*, *Sorghum*).

Fibre crops: *Cannabis sativa* (hemp), *Crotalaria juncea* (sun hemp), *Hibiscus sabdariffa* (rosella), *Corchorus capsularis* (jute), *Hibiscus cannabinus* (kenaf), cotton (*Gossypium* sp.).

Dye crops: *Carthamus tinctorius* (also an oil crop), *Indigofera suffructicosa* and *I. tinctoria*.

Oil crops: *Ricinus communis*, *Carthamus tinctorius*.

Commercial crops and vegetables: tobacco, tomato, chillies (*Capsicum*), onions, cabbage and other vegetables (Cucurbitaceae).

Tuber crops: sweet potatoes, cassava, potatoes, *Colocasia esculenta* (taro).

New cropping patterns should first be tested on pilot farms.

If, however, double cropping with rice is practised, then it is necessary to ensure that both crops are planted strictly according to a time schedule which allows for an aeration period between the main season and the off-season of at least six weeks and to ensure that the planting takes place at the same time in all irrigation blocks, so that the water need not be maintained in the fields longer than is necessary. Towards the end of the main season, irrigation should be stopped in time for the standing rice crop to exhaust the water remaining in the field and the available water from the top soil, so that aeration may be effective. Only short-term and medium-term varieties should be used, in order that sufficient time can be allowed for an aeration period. Any increase in diseases and pests which might result from double cropping with rice should be controlled by modern chemical means. Two rice crops will remove more nutrients from the soil than one crop did in the past, and an adequate application of fertilizers will be necessary to maintain a good yield.

To make planting strictly according to a time schedule possible, the introduction of mechanical equipment for soil tillage should be encouraged.

Double cropping of rice is possible in the Cho-Shui delta. In the northern part, double cropping is even followed by short-duration crops or vegetables. The cultivation and growth of such a crop will intensify the very much needed aeration of the soil. In the Nobi delta, wheat, barley or rape seed are grown during winter.

Improvement of soil conditions

The improved water control of the delta makes a more intensive use of land possible. At the same time, other measures have to be taken to increase production and to maintain a high yield capacity in the soil. The most important are briefly described below.

Fertility. Flood control and or irrigation measures, in the first place, lead to a decrease in the annual supply of

fresh sediment and corresponding minerals dissolved in the river water.

Secondly, the more intensive cropping pattern with high-yield varieties of rice and other crops exhausts soil mineral supply at a more rapid rate.

The diminished annual supply of nutrients and the increased need for them on the part of the crops is a dual reason for the application of fertilizers or manure in adequate quantities.

Fertilizers and manure will be more effective under proper irrigation and drainage conditions.

Soil structure. As long as rice is the only crop grown, soil structure does not play such an important role in plant production. In the case of multiple cropping either with a double rice crop or with rice alternated with other crops, more attention has to be paid to the maintenance and improvement of the soil structure. By the application both of compounds for soil improvement like lime, gypsum, etc., and of organic manure (stable manure, green manure), the structure and biological life of the soil may be improved. The compound to be used depends on the specific circumstances of crops and soils. If green manure crops (Leguminosae) are inserted into the crop rotation, they can be incorporated either in the soil for rice or the soil for dry crops, depending on crop requirements and soil redox potential.

In the case of the application of fertilizers, the soil moisture and irrigation conditions will determine, for instance, the form in which the nitrogen will have to be present in the fertilizer.

The effect of phosphate will increase under waterlogged conditions.

Reduced conditions may prevent absorption of potassium.

These examples demonstrate that the changed conditions may not only require higher amounts of fertilizers and the more frequent application of fertilizers and manure but also a different kind of fertilizer or method of application.

Soils like the potential cat-clays, organic soils and saline soils already mentioned require special treatment.

Other improved agricultural techniques which are not specifically designed for tropical deltas should, however, also be applied, if the highest effect is to be obtained. Of these, the selection of seeds, weed control and the use of pesticides may be mentioned.

Other improvements

When the irrigation and drainage conditions are being improved, it is often also possible to improve the infrastructure of the various areas in the delta without high additional cost by providing means of communication by road and water and an energy and potable water supply. A good infrastructure is essential for the development of the delta.

A comprehensive land consolidation scheme should remove the disadvantage caused by the subdivision and parcelling of the small holdings. Land consolidation should be planned concurrently with the planning of the water control and infrastructure of the area.

Improved conditions in this respect will allow for less complicated and better water control by the farmer and more effective use of labour and will increase the possibilities for multiple cropping and mechanized farming.

An example of land consolidation is found in the Cho-Shui delta.

Social and economic problems will be created by the change in conditions in the delta. They will have to be solved by the provision of an adequate extension service, co-operation between farmers, good credit facilities and proper marketing conditions.

Résumé

Problèmes scientifiques des deltas de la zone tropicale humide et leurs implications (G. A. W. van de Goor)

La population assez nombreuse que comptent les deltas de la zone tropicale humide s'explique par un ensemble de conditions climatologiques, hydrologiques et pédologiques.

Ces conditions ont favorisé la culture du riz en sol humide, qui a permis de nourrir cette population en permanence pendant des siècles.

Les deltas se distinguent des autres régions de la zone tropicale humide par les caractéristiques suivantes : l'existence d'un sol à grain très fin résultant de la sédimentation qui se produit pendant les crues annuelles du fleuve, lesquelles sont influencées, à l'extrémité inférieure du bassin, par les marées; les problèmes que créent naturellement les marées, problèmes de la salinité et de l'acidité du sol; la faible élévation, la légère inclination du terrain et, en conséquence, le niveau peu profond de la nappe d'eau souterraine.

Ces caractéristiques rendent le sol assez impropre à presque toutes les cultures, du double point de vue physique et agro-hydrologique.

Mais, si les conditions naturelles ne sont pas sensiblement modifiées, ces terres inondées et marécageuses offrent divers avantages pour la culture du riz en sol humide.

Les plus importants sont les suivants : la facilité

relative avec laquelle on peut empêcher les plantes rampantes de pousser, l'abondance de la réserve d'eau, la protection que la culture du riz apporte contre l'érosion, la prévention partielle ou totale de l'infiltration, la présence d'éléments nutritifs pour les plantes et celle de limon, les variations de la solubilité, de la quantité et de la forme de ces substances nutritives que crée le faible potentiel redox, et la fixation de l'azote par les algues cyanophycées, dont la croissance est favorisée par l'inondation de la rizière. On peut ajouter à cela que le labourage en sol humide, qui est souvent pratiqué, a peut-être un effet moins destructeur pour le sol que le labourage à sec.

De plus, le riz est moins sensible au déséquilibre du sol parce qu'il peut transporter de l'oxygène de ses feuilles à ses racines, parce que l'eau est en abondance et que le sol est à l'état de boue. Il existe en outre plusieurs moyens d'adapter la culture du riz à la profondeur de la rizière et à l'élévation du niveau de l'eau ainsi qu'aux conditions de salinité, d'acidité et de réduction du sol. Les principaux types qui témoignent d'une grande adaptabilité sont le riz flottant, le riz de plaine et le riz de montagne.

En raison de la faiblesse des précipitations pendant la saison sèche et de la dureté du sol qui en résulte alors, il est presque impossible, après la culture du riz, d'entreprendre des cultures en terre sèche avec les moyens dont on dispose.

Pour améliorer les conditions pendant las aison humide, c'est-à-dire la principale pour le riz, et pendant la saison sèche, c'est-à-dire secondaire pour le riz et autres cultures, il faut connaître exactement les besoins en eau. Pour que la culture du riz soit profitable, il est important que les installations d'irrigation et de drainage soient efficaces.

Comme le riz reste la seule culture pendant la saison humide et même, parfois, pendant la saison sèche, les besoins particuliers de cette plante en eau déterminent les mesures de régulation de l'eau dans les rizières.

La quantité nette d'eau nécessaire aux rizières devrait être étudiée dans des régions pilotes, pour lesquelles on pourrait dresser un bilan hydrique exact. Les pertes d'eau y sont dues principalement à l'évapotranspiration et à la percolation. L'évapotranspiration du riz se produit généralement au taux le plus élevé, c'est-à-dire correspondant à l'évapotranspiration potentielle.

Si l'on dispose de données climatologiques, on peut calculer la valeur de l'évapotranspiration par les diverses méthodes mathématiques, notamment celles de Penman. On peut aussi évaluer facilement et exactement l'évapotranspiration, dans les rizières mêmes, au moyen d'une sorte de lysimètre. La percolation dans les rizières des deltas doit être faible en raison, soit du système d'irrigation, soit de la culture du sol, soit de la combinaison des deux éléments.

La profondeur d'eau tolérée par le riz peut dépasser dix centimètres; des profondeurs plus grandes ont généralement des effets défavorables. L'influence de la profondeur de l'eau varie selon l'époque et la phase de croissance. L'immersion totale, si elle dure plus de quelques jours, peut être très néfaste et doit être évitée, surtout pendant la phase de reproduction.

Une méthode est indiquée pour le calcul du volume d'eau nécessaire chaque jour pendant une certaine période de présaturation. Pendant cette période, les besoins en eau sont généralement plus élevés qu'après la transplantation du riz.

L'état du sol peut exiger le drainage de l'eau des rizières. Les besoins en eau des cultures sèches sont différents, car l'évapotranspiration est plus faible, mais ces cultures peuvent nécessiter un drainage plus profond.

L'utilisation mieux contrôlées de l'eau peut modifier l'utilisation des terres et la répartition des cultures.

Il est parfois possible de cultiver le riz et une autre plante si l'on veille soigneusement à l'aération du sol.

Pour tirer le plus grand profit de la meilleure utilisation de l'eau, il serait utile d'améliorer en même temps l'infrastructure de la région et les conditions de l'agriculture en recourant, le cas échéant, aux moyens suivants : consolidation des terres, usage d'engrais, emploi de semences sélectionnées et de parasiticides, et emploi de machines agricoles.

Discussion

V. N. Nagaraja. Could you give more elaboration about the use of sea-water to leach the harmful products from the soil?

G. A. W. van de Goor. The acids formed are flushed away by using sea-water during periods when no fresh water is available for that purpose. This method is practised in Sierra Leone and more information is available in publications of the West Africa Rice Research Station.

G. A. Prowse. What is the reason why yields of rice in countries like Australia (N. S.W.) are much higher than in the humid tropics?

G. A. W. van de Goor. There are various reasons: first the longe days in the first countries; secondly the greater use of fertilizers; thirdly, the often practised rotation of crops.

G. A. Prowse. Has Dr. van de Goor visited the Riverina in Australia where, with 16 inches annual rainfall, more rice is grown than in Malaya?

G. A. W. van de Goor. The conditions there are favourable, with high radiation and lower temperatures at the right time, as in Iran.

V. N. NAGARAJA. Dr. van de Goor's paper is a most useful contribution to this symposium in as much as it throws immense light on the problem of water management in the context of agricultural needs and maintenance of soil fertility.

Based on the author's long experience in the International Institute for Land Reclamation and Improvement in the Netherlands, the paper provides conclusions applicable to the deltaic areas in the Asian regions as well.

In particular, the Sierra Leone and the Viet-Nam technique of leaching cat-clay soils is a good example of water management.

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Nutritional status of East Pakistan population

K. Ahmad

During the past two years, a nutrition survey has been under way in East Pakistan as a collaborated effort between the Government of Pakistan and the National Institutes of Health of the United States of America. Unicef and FAO also lent their support to this programme by contributing technical assistance and some equipment. The University of Dacca through the Department of Biochemistry acted as a base for the operation and made available the services of its personnel and laboratories.

The survey was conducted on multi-stage randomly selected samples in urban and rural areas of East Pakistan. It was a triphasic plan comprising (a) assessment of family food consumption; (b) clinical examination for signs of malnutrition and related diseases; and (c) biochemical analyses of urine and blood to detect subclinical diseases. Urban and rural areas from each of the seventeen districts of East Pakistan were included in this survey.

A team of dieticians, clinicians and field biochemists travelled to selected locations to obtain data on food composition using the 24-hour food weighing method. This was supplemented by a questionnaire as to the amount and kind of food consumed outside the home (such as at restaurants or stalls) during the period under study. Physical examinations were made as regards height and weight; clinical signs of nutritional deficiencies were investigated according to the standard criteria of ICNND and WHO. About 10 per cent of the individuals given brief clinical examination were subjected to detailed examination including biochemical examination of blood and urine.

So far we have examined 3,000 families for food consumption and about 18,000 subjects were examined clinically. Biochemical examinations were carried out on 2,200 samples of blood and urine.

From the food consumption data we calculated the mean *per capita* intake for the rural population to be 2,040 cal. per day. The figure for urban population is extremely low, 1,630 cal., but one must take into consideration the high children-to-adult ratio of the population groups under study.

The protein intake is calculated to be 50 g. for the rural population and 45 g. for the urban population while 21 per cent of the protein intake of the urban population is of animal origin, the corresponding figure for the rural population is 12 per cent.

Our data show a dietary fat intake of 14.8 g. and 22.9 g. corresponding to 6.5 per cent and 12.8 per cent cal. intake for the rural and urban populations respectively. The percentage of animal fat is 13 and 24 per cent.

When dietary intake is considered in respect to food groups one would see the position as that shown in Table 1.

TABLE 1. Dietary intake

	Fats and oils	Meat and animal products	Fruits and vegetables	Legumes	Cereals and starch
	%	%	%	%	%
Rural	1	9	11	5	74
Urban	3	14	15	8	60

The distribution of calories between fat, protein and carbohydrate is shown in Table 2.

TABLE 2. Distribution of calories

	Fat	Protein	Carbohydrate
	%	%	%
Rural	6	10	84
Urban	13	11	76

We have calculated the intake of vitamin A (vegetable and animal sources) from our dietary figures.

The values for rural and urban populations are 460 I.U. and 1,750 I.U. respectively. In terms of the recommended allowance of 4,330 I.U. a day, it would appear that the rural population only gets 11 per cent and the urban population 40 per cent of this amount. The intake of riboflavin is 0.36 mg. and 0.51 mg. for rural and urban populations respectively. In terms of the recommended allowance of 1.55 mg. per day, these intake values represent 23 per cent and 33 per cent for the rural and the urban populations respectively. The calculated dietary values for ascorbic acid are 15 mg. for the rural and 31 mg. for the urban population. These values are only 22 per cent and 44 per cent of the recommended allowance of 71 mg. per day.

So far we have considered the intake of only two minerals, iron and calcium. According to our findings the rural population gets 7.1 mg. and the urban 8.6 mg., which respectively represent 65 per cent and 79 per cent of the recommended allowance of 10.9 mg. a day.

The intake figures for calcium are 215 mg. for rural and 200 mg. for the urban population. In terms of the United States standard of 1,050 mg. per day these represent 20 per cent of the recommended allowance.

As stated earlier, blood and casual urine samples were collected from approximately 10 per cent of the population examined clinically. These samples were carefully collected, packed in an ice box and shipped from the field to the laboratory at Dacca by the quickest transport. From most of the survey areas, these samples arrived within 48 hours of collection. The analytical methods are mostly those described in the ICNND manual.[1] In certain cases, hematocrit was carried out in the field where trichloroacetic acid extract for vitamin C was always prepared.

The urine samples were analysed for excretion of riboflavin and thiamine and expressed in terms of creatinine excretion. From all localities the samples showed that excretion of riboflavin was below the acceptable values. Urinary excretion of thiamine was low in only 1.8 per cent of the groups studied.

Table 3 presents the values of serum vitamin A in four different groups according to the physiological status of male adults, non-pregnant and non-lactating female adults, pregnant and lactating women and children 5-15 years of age.

Serum ascorbic acid levels were below 0.2 mg. in 26.4 per cent cases while over 26 per cent low values were found during the dry season.

Serum globulin levels were normal or high in 95.2 per cent cases where albumin levels were below 3 g. per cent in 22 per cent of the population sampled. Serum total cholesterol values in adult males ranged from 56.8 per cent to 195 mg. per cent with 45.2 per cent below 120 mg. per cent; 24 per cent of the population had haemoglobin levels below 11 g. and 8 per cent below 9 g. The anaemia appeared to be simple iron deficiency anaemia.

1. "Biochemical methods." Chapter IV of *ICNND Manual.*

TABLE 3. Serum vitamin A levels

Group	0-10 µg. per 100 ml.	10-20 µg. per 100 ml.	20-30 µg. per 100 ml.
	%	%	%
Males and females, 5-14 years	8	41	34
Females (pregnant and lactating)	7.5	35	35
Males, 15 years and older	6.5	21	35
Females, 15 years and older (non-pregnant and non-lactating)	5.5	25	38

As in most developing countries the growth charts indicate a combined protein-calorie malnutrition. Clinical vitamin A deficiency is suggested by 3 per cent incidence of follicular hyperkeratosis by the skin, 1 per cent of those studied had Bitot's spot. Children under 15 years exhibited wrinkling of the conjunctiva in 44 per cent of cases. Clinical vitamin B_2 deficiency was suggested by 13 per cent incidence of angular stomatitis and cheilosis and 6 per cent incidence of papillary atrophy of the tongue. Scorbutic gums were noted in 3 per cent of cases but there was no real scurvy.

The outstanding findings of the survey are that the population suffers from a serious deficiency of vitamin A and vitamin B_2. This is supported by both clinical, dietary and biochemical evidence. While the general protein calorie deficiency is widespread in all developing countries, we believe that these two deficiencies are rather unique in East Pakistan. We also believe that these two deficiencies can be removed by encouraging the population to eat coloured and leafy vegetables.

Judged by the United States standards of recommended allowance, our intake of 15 mg. of ascorbic acid a day is of course very low. However, since there is no scurvy, one might conclude that 15 mg. could be considered just enough. My personal view is that the criteria for considering a certain level of vitamin C

TABLE 4. Comparative figures on the nutrition status

	East Pakistan	Viet-Nam	Thailand
Calories	2,041	2,526	1,821
Protein	50 g.	75 g.	49 g.
Calcium	215 mg.	400 mg.	280 mg.
Iron	7 mg.	21 mg.	10 mg.
Vitamin A	462 I.U.	2,884 I.U.	1,780 I.U.
Riboflavin	0.36 mg.	0.25 mg.	0.40 mg.
Vitamin C	15 mg.	30 mg.	34 mg.

as the critical amount have not been determined. Considering a substance like vitamin C, which has more than one biochemical function in the human body, it would not be fair to consider its requirement in terms of one criterion only. This line of thinking perhaps applies to the case of many nutrients.

The work discussed here is the result of the combined efforts of all those engaged in the conduct of a nutrition survey in East Pakistan, each playing his own important role in the work. The results are presented in Table 4 on behalf of all.

Résumé

Valeur nutritionnelle des aliments de la population du Pakistan-Oriental (K. Ahmad)

Au cours des deux dernières années, le gouvernement du Pakistan, en collaboration avec les instituts nationaux de la santé (National Health Institutes) des États-Unis, a entrepris une enquête sur la valeur nutritionnelle des aliments de la population au Pakistan-Oriental. La FAO et l'Unicef ont contribué à la mise en œuvre de ce programme en fournissant une assistance technique et une partie du matériel d'équipement. Cette enquête a porté jusqu'ici sur des groupes choisis au hasard dans les régions urbaines et dans les régions rurales.

L'auteur indique les résultats obtenus après examen clinique de 18 000 sujets environ.

Discussion

G. A. Prowse. Could I ask whether the vitamin A deficiency is due to feeding habits?

K. Ahmad. Yes, because the people do not eat fish liver or other foods containing vitamin A.

Population of East Pakistan

A. M. Patel

East Pakistan is one of the most densely populated regions of the humid tropics. The population of over 50 million (1961) is crowded into an area of 55,125 sq. miles.[1] Unlike many other densely populated areas of the world, East Pakistan's population is mainly agricultural and rural and its rapid increase is a great strain on the country's limited agricultural resources.

GROWTH OF POPULATION

The population in the early days of British rule was not very large. Rennel's map shows the lower part of the delta empty of villages, with the words "depopulated by Maghs" written across it.[2] The first regular, though not very accurate, census was taken in 1872. The 1881 census revealed a total population of 25 million for the area now constituting East Pakistan.

TABLE 1. Growth of population in East Pakistan, 1881 to 1961

Census year	Population (thousands)	Density per sq. mile	Variation %
1881	25 086	455	—
1891	27 103	491	+ 8.1
1901	28 927	525	+ 6.6
1911	31 555	572	+ 9.0
1921	33 254	603	+ 5.3
1931	35 604	645	+ 7.0
1941	41 997[1]	761	+ 17.9
1951	42 206	761	+ 0.1
1961	50 840	922	+ 21.2

1. Due to the impending partition of the country into India and Pakistan, both Hindus and Moslems were over-enumerated in the 1941 census, thus inflating the figure for total population. The probable figure would be about 38 to 39 million.

Sources: Census of Pakistan, 1951, Vol. 3, *East Bengal*, p. 32; N. Ahmad, in: *Economic Geography of East Pakistan*, London, 1958, p. 289 (for population figures of 1881 and 1891); *Population Census of Pakistan*, 1961, Bull. No. 2, p. 13.

1. Excluding rivers the area of East Pakistan would be 51,921 sq. miles.
2. *Census of India*, 1911, Vol. V, Part 1, *Calcutta*, p. 61.

The population of East Pakistan has doubled in a period of 80 years, from 25 million in 1881 to 50 million in 1961. The increase in numbers over this period has not been uniform; in the 50 years between 1881 and 1921, population increase varied from 2 million to 2.5 million per decade, except in the decade 1911-1921 when the increase in numbers was less than 2 million (1.7 million). From 1931 onwards the growth of population has been more rapid and has increased by 15 million over the last 30 years, of which 8 million were added in the last decade.

Rate of increase

The rate of increase of population over the years has varied, depending upon years of good harvests, food shortages, famine and epidemics. In the period before 1911 there were years of normal growth accompanied by the usual mortality due to epidemics. The rate of increase during this period was slightly less than 1 per cent per annum. The decade 1911-1921 shows the lowest increase (0.53 per annum) due to high mortality from the influenza epidemic of 1918. In view of the obvious over-enumeration in the 1941 census, it is not possible to examine the rates of increase for the decades 1931-1941 and 1941-1951. The decade 1931-1941 was a normal one by East Pakistan standards and the growth may have been above 1 per cent annually, but during the period 1941-1951 the rate of increase must have been low, not necessarily as low as the table indicates, because of the high mortality, variously estimated between 1.7 million and 2.5 million, of the Bengal famine of 1943 and the migration of populations that followed the partition of the country in 1947. The decade 1951-1961 shows the highest rate of increase: 2.1 per cent per annum.

This annual increase of 2.1 per cent is due to a decline in the mortality rates resulting from increasing control of diseases and famines, "the two major controlling factors in the growth of population" (Chandrasekhar,

1961). Part of this increase may also be attributed to the fact that in this period the percentage of Moslems to total population increased from 76.8 per cent to 80.4 per cent. Moslems have always had a higher birth rate than Hindus and Mohiuddin Ahmed (1962) estimates the birth rates in 1951 for these two communities of East Pakistan at 61.9 and 48.1 respectively. Within the province the rate of increase during the period 1951-1961 has not been uniform everywhere. Ten out of the 17 districts showed an annual increase ranging from 1.5 to 2.5 per cent, two between 2.6 and 3.0 and three between 3.1 and 3.4 per cent[1]. Generally speaking districts with higher densities had a lower rate of increase than districts with lower densities.

The rate of increase of East Pakistan's population is, however, not high when compared with other countries. East Pakistan doubled its population in 80 years whereas the United States doubled its population in 30 years after the Civil War; the population of England and Wales increased by 125 per cent from 1811 to 1871, while Japan's population increased by about 100 per cent in about 50 years (Trewartha, 1960). The present rate of increase of population in East Pakistan is, therefore, not high when compared with the past rates of increase of many other countries. East Pakistan is still in the second phase of the demographic cycle,[2] viz., the early expanding phase, and can therefore be expected to maintain the present rate of increase for some time to come, before its population begins to level off. But unlike other areas or countries that have passed this phase of the demographic cycle, East Pakistan suffers from certain disadvantages, such as an already existing large population and restriction on emigration.

Though the rate of increase is not high, the net increase of 8 million in 10 years (1951-1961) on an already large population is substantial. Pressure on land is high—about half the population is in the range of 1,000 to 1,200 persons per sq. mile and outlets for emigration (Assam and Burma) are closed. This large increase of about 1 million annually is therefore a problem, especially in view of the limited agricultural resources.

Birth and death rates

The official figures for birth and death rates suffer from under-registration. Registration of births and deaths was introduced in Bengal in 1892, but the figures are far from correct. Davis (1951) estimated the percentage of registration of the births in Bengal for the period 1926-1930 at 58.4. An inquiry during the 1951 census revealed that out of a total of over 1.8 million births only 570,000 were registered.[3] The same is true of death registration to some extent. The official figures for the four years 1952-1955, for the crude birth and death rates per thousand of population, were 19.00 and 10.16 respectively.[4] These rates give a natural increase of only 1 per cent annually as against the actual annual increase of 2.1 per cent for the decade 1951-1961. There are, however, estimates of birth and death rates available from other sources.

TABLE 2. Estimates of crude birth and death rates of East Pakistan

Source	Birth rate (per 1,000 population)	Death rate (per 1,000 population)	Years
Official[1]	19.00	10.16	Av. 1952-55
A. S. Mohiuddin Ahmed[2]	58.70	48.10	1951
K. J. Krotki[3]	53.60	32.00	1961
Population growth estimation[3]	44.46	16.17	1962

1. *Statistical Abstract for East Pakistan, Dacca*, Vol. V, 1958, p. 60-62.
2. A. S. Mohiuddin Ahmed (1962), p. 145 and 386.
3. Sultan S. Hashmi, *Main Features of Demographic Conditions in Pakistan*, Karachi, 1962, p. 121, 129 and 147.

Mohiuddin Ahmed and Krotki estimate high birth and death rates, though Krotki's figure for the death rate is much lower. When compared to Chandrasekhar's estimate for the crude birth and death rates for India, for the years 1951-1956, of 40.7 and 25.9 respectively, both Mohiuddin Ahmed's and Krotki's estimates appear to be high. The crude birth rate as estimated by the Population Growth Estimation Unit of 1944-1946 is close to Davis' (1961, p. 69) figure for the sub-continent of 45 births per thousand population in 1931-1941. It therefore appears that the estimates of the Population Group Survey (44-46 per thousand population) are probably more correct. Allowing for an annual increase of 2.5 per cent, the crude death rate then would be between 21 and 23 per thousand of population, which does not differ greatly from the estimates of Chandrasekhar for India.

With emigration playing an almost insignificant role the population growth of East Pakistan has largely been due to natural increase, viz., excess of births over deaths. Mohiuddin Ahmed (1962, p. 275) believes that the birth rate for East Pakistan has more or less remained constant and that there has been no appreciable decline during the last few decades. Chandrasekhar (1961, p. 26) holds an almost similar view regarding India and maintains that there has been only

1. *Population Census of Pakistan*, 1961, Bull. 2, p. 10.
2. The five phases of the demographic cycle are: (a) the high stationary phase (high birth rates and high death rates); (b) early expanding phase (high birth rates and low and declining death rates); (c) low expanding phase (declining birth and death rates); (d) low stationary phase (low birth and death rates); (e) declining phase (excess of deaths over births). See S. Chandrasekhar (1956).
3. *Census of Pakistan*, 1951, Vol. III, p. 33.
4. *Statistical Abstract for East Pakistan, Dacca*, Vol. V, 1958, p. 60-62.

a small decline in the birth rates during the last fifty years. A recent study published in Princeton by Coale and Hoover (1959) also confirms that there has been no more than a minor decline in India's birth rate.

Mohiuddin Ahmed's view regarding an almost constant birth rate in East Pakistan can therefore be accepted tentatively. The only explanation then for the expanding population of East Pakistan is a decline in the death rates. As no reliable estimates for the death rates of East Pakistan for the preceding decades have been attempted, Davis' estimates for the sub-continent may be used at least to indicate the tendency for a declining death rate.

TABLE 3. Estimates of crude death rates for India-Pakistan, 1881-1941

Decade	Death rate (per 1,000 population)	Decade	Death rate (per 1,000 population)
1881-1891	41.3	1911-1921	48.6
1891-1901	44.4	1921-1931	36.3
1901-1911	42.6	1931-1941	31.2

Source: K. Davis, *Population of India-Pakistan*, p. 36.

Chandrasekhar (1961, p. 27) has calculated the crude death rates for India for the period after 1941 and he has found that the tendency for a decline in the death rate has continued. His estimates for India are: 1941-1950, 27.4 deaths per 1,000 population; 1951-1956, 25.9 deaths per 1,000 population.

The decline in the death rates in East Pakistan and also in other parts of the sub-continent is due mainly to an improvement in public health conditions.[1]

Age and sex distribution

A striking feature of the population of East Pakistan is the large proportion of children under 10 years of age. The percentage of the age group under 10 years of age rose from 30 of the total population to 37 in 1961.

The age distribution in 1951 formed a broad-base pyramid rapidly tapering with age. By 1961 there was a further widening of an already broad base which means that for some time to come the growth of population will be rapid. About 47 per cent of the population in 1961 was under 15 years of age as compared with 42 per cent in 1951. A little more than 40 per cent of the population in 1961 was between 15 and 44 years, as compared with 44 per cent in 1951. The shrinkage of the population in the age groups 10-14 and 15-19 is surprising and there seems to be no ready explanation for it.[2] It appears that the enumeration of these age groups was inaccurate. The increase in the percentage of population over 60 years, though only by 1 per cent, is significant, for it indicates greater longevity.

TABLE 4. Percentage of males and females by age for East Pakistan, 1951 and 1961

Age group	1951			1961		
	Both sexes.	Male	Female	Both sexes	Male	Female
0-9	29.27	28.35	30.69	36.97	35.86	38.16
10-14	12.63	13.47	11.70	9.14	9.91	8.32
15-19	9.96	9.40	10.38	7.68	7.29	8.10
20-24	8.29	7.81	8.81	7.50	6.92	8.12
25-44	25.42	25.86	23.35	24.42	24.70	24.13
45-59	9.61	10.44	8.70	9.07	9.07	8.32
60 and over	4.43	4.66	4.17	5.22	5.55	4.86

Source: Population Census of Pakistan, 1961, Bull. No. 3, *Karachi*, p. VIII.

The sex ratio has usually shown an excess of males over females. The sex ratio over the last few decades has not varied much: 105-110 males per 100 females. It is, however, difficult to account for this deficiency of females particularly when in the age group 0-9 there is an excess of females. But in this age group the excess of females over males is confined only to children below 4 years. In the age group 4-9 and subsequent age groups the ratio is reversed. According to Chandrasekhar the probable explanation "for the paucity of females appears to be that though the female infant is definitely better equipped by nature for survival than the male, the advantages she has at birth are probably neutralized in infancy by comparative neglect and in adolescence by the strain of bearing children too early and too often" (Chandrasekhar, 1961, p. 39). Child marriages still persist, mainly in the rural areas, and in 1961 about 30 per cent of the girls in the age group 10-14 were married.[3] The sex ratio is much lower in rural areas (106 males to 100 females) as compared with the urban areas (142 males to 100 females). The larger urban centres have a higher ratio of males to females as compared with smaller urban centres. This large excess of males in the urban population is normal in a region where the migration from the rural areas to the urban areas consists mainly of males.

1. In many other non-Asian countries similar declines in the death rates have also taken place, but they were due to economic development of the regions, which invariably led to a decline in the death rates. According to the "theory of demographic transition" high birth and death rates are characteristics of an agrarian peasant economy and economic development leads to a decline in the birth and death rates of such areas. Coale and Hoover doubt the precise applicability of this theory as regards death rates, as many low-income areas have without altering their present agrarian structure been able to reduce their death rates mainly by better public health measures. See Coale and Hoover, (1959), p. 9-17.

2. *Census of Pakistan*, 1961, Bull. No. 2.

1. *Population Census of Pakistan*, Bull. No. 3. pp. 4-5.

Rural and urban growth of population

In 1951, 95.6 per cent of the total population of the province was rural as compared with 94.8 per cent in 1961. Urban population increased from 18.4 million in 1951 to 26.4 million in 1961. The population of all the towns increased during the decade by 43 per cent; the corresponding increase of population in the urban centres with populations above 1 million was a little higher: 46.

The four largest urban centres in 1961 were Dacca (556,712), Chittagong (364,205), Narayanganj (162,054) and Khulna (127,970); slightly less than half of the total urban population were living in these four centres.

TABLE 5. Variation in the number of towns in East Pakistan, 1911 to 1961

Class of town	1961[1]	1951	1941	1931	1921	1911
Class I (population over 1 million)	4	2	1	1	1	1
Class II (25,000 to 1 million)	20	17	17	9	7	2
Class III (10,000 to 24,999)	22	20	20	21	20	23
Class IV (5,000 to 9,999)	21	18	19	17	13	13
Under 5,000	10	7	3	11	10	10
	77	64	60	59	51	49

1. The definition of urban centres in 1961 was more liberal than in 1951.

Sources: Census of Pakistan, 1951, Vol. 3, p. 59; *Population Census of Pakistan*, 1961, Bull. No. 2, p. 68-73.

The number of towns of over 1 million population has increased from two to four in the last decade. An increase of two to three in each class of urban centre indicates a rather steady growth in the number of urban centres.

The large rural population is characteristic of an economy that is mainly agricultural with little industrialization. East Pakistan has always been predominantly rural with tiny and almost self-sufficient village communities. Urban centres were few in number and were mostly administrative towns with commerce and small industries attached to most of the centres. This is true to a large extent of most of the small towns even today. With an increase in commercial cropping, particularly jute, and also due to improved communications and development of large-scale industries, the commercial and industrial functions have gained increasing importance. Dacca, Chittagong, Narayanganj and Khulna are examples of this latter type of urban centre. They have been attracting population not only from the rural areas but also from other urban centres, both from within the province and from West Pakistan.

DENSITY AND DISTRIBUTION OF POPULATION

In 1961 the density of population was 922 persons per sq. mile and if the river areas were excluded the density would be 979. If only cultivated land is taken into consideration the density would be 1,300 per sq. mile. There is considerable variation of population densities within the province. The areas of maximum overcrowding have very high densities: 1,500 to 2,000 per sq. mile in the rural areas along the lower Padma (Ganges) and Meghna with some areas having still higher densities of 2,000 to 2,500. On the other hand in the Chittagong hill tracts there are only 76 persons per sq. mile. In the province as a whole, slightly less than half of the total population was in the density range of 1,000 to 1,200 per sq. mile.[1]

The area with the greatest concentration of population extends in an almost north-south direction along the Jamuna (Brahmaputra), the lower Padma and Meghna rivers and includes towards the south the coastal strip of the Chittagong district. Almost everywhere densities are high and the figures rarely fall below 1,000 persons per sq. mile. Within this belt there are a few areas with particularly high densities. These are from north to south: (a) the flood-plains of the lower Jamuna in Pabna district, over 1,500 persons per sq. mile; (b) the tract of country above the junction of the lower Padma and the Meghna, in Dacca district, including the urban areas of Dacca and Narayanganj (densities in the rural areas vary between 1,500 and 2,000 persons per sq. mile and in some areas exceed 2,000); (c) the lands east of the Meghna (Comilla and Noakhali districts) which have the highest rural densities for any large single rural area of East Pakistan (densities are between 1,500 and 2,000 and some parts of Noakhali district have more than 2,000 persons per sq. mile); (d) the narrow coastal strip of the Chittagong district, including the urban centre of Chittagong and the surrounding rural areas (most areas have above 1,500 and one *thana*[2] has more than 5,000 persons per sq. mile).

There are two other thickly-populated areas linked with this north-south belt, one lies to the south-west, between the Madhumati and the lower Padma-Meghna (the districts of Faridpur and Barisal) and the other to the north-east along the old Brahmaputra in Mymensingh district. In the former area densities are above 1,000 persons, increasing to over 1,500 persons per sq. mile eastwards. In the latter area (old Brahmaputra) densities are above 1,000, but near the confluence of the old Brahmaputra and Meghna they increase to 1,500 to 2,000 persons per sq. mile.

1. *Population Census of Pakistan*, Bull. No. 2, p. 13.
2. *Thana* (police administrative unit) is one of the lower units in the administrative hierarchy of the province. Their areas generally vary between 75 and 250 sq. miles, with a large number in the range of 100-150 sq. miles. *Thanas* also serve as useful units for census purposes.

The rest of the province has medium (800 to 1,000) to lower densities (500 to 800). One of the medium density areas is the western part of a province. This belt extending from north to south includes areas of lower densities like the Barind. In the extreme north some parts have higher densities (over 1,000) but over most parts densities are low, particularly in the Barind (500 to 700) and the low-lying areas north of the Padma. In the area south of the Padma (Kushtia, Jessore and Khulna districts) densities are mostly between 600 and 800, but some areas have over 800 to 1,000 and in Khulna district some parts have over 1,000 persons per sq. mile. Jessore and Kushtia districts, which had an almost stationary or declining population, showed a significant increase of 34 and 32 per cent respectively during 1951-1961. Two other areas of medium densities are the Madhupur tract and Sylhet district, both lying east of the Jamuna. The first has densities varying between 700 and 900 persons per sq. mile, while Sylhet district has areas with as low as 350 persons per sq. mile, but over most areas it is 600 to 800 persons per sq. mile. Some areas between the Surma and Kusiyara rivers, and in certain parts of south Sylhet also have higher densities of over 1,000 persons per sq. mile. The Chittagong hill tracts, the southern portions of Chittagong district and the Sunderbans forest area of Khulna district are sparsely populated.

The density of population in East Pakistan is largely the result of geographical conditions. There appears to be a direct relationship between the agricultural capacity of the land and the density of population. The agricultural productivity of the land in turn depends upon such factors as soil, land levels and extent of inundations, double cropping, nature of crops grown, etc. Most of the eastern and south-eastern parts of the province consist of actively built riverine lands with free and unobstructed drainage, subjected to heavy seasonal inundations and consequent replenishment of soils. The floods flush the lands and the incidence of malaria and other epidemics is low. Inundation by rivers, therefore, serves a dual purpose in the demographic set-up; it produces fertile soils and provides healthier living conditions giving rise to high densities of population. On the other hand most of the western part of the province is an area of moribund rivers and deteriorated drainage with no widespread inundations. Marshy areas are quite extensive and living conditions are less healthy. The soils are also less fertile. Parts of Kushtia, Jessore and Rajshahi districts have suffered from an arrested growth of population due to malaria and other epidemics since the middle of the last century. The areas of dying rivers do not show an impressive increase in population and are also less densely populated than the areas of active rivers.

The relative levels of land surface also give rise to variations in densities. The river levees, because of their relative height above flood level, attract settlements, and the population is mostly concentrated on the levees, avoiding the low-lying lands. On the river levees the soil texture is also lighter than in the inter-levee areas where the soils are heavier. Consequently the cropping pattern is different, on the levees crops such as jute are grown while the inter-levee areas are mostly under paddy cultivation. The soil type also partly determines the extent of double cropping. The silt loam and sandy loams generally retain sufficient soil moisture to allow double cropping.[1] On the other hand the old alluvium of the Barind and Madhupur with its lateric red earths are one-crop lands. Besides double cropping, the cropping pattern also, to some extent, influences population densities. According to Nafis Ahmed (1958, p. 276-287)[2] exclusively paddy-growing areas have usually lower densities than areas with both paddy and jute cultivation.

POPULATION AND FOOD SUPPLY

While population has been increasing at the rate of about 1 million annually, the acreage under food crops has increased at a much slower rate (see Table 6).

TABLE 6. Area under food crops in East Pakistan, 1950-1951 to 1959-1960 (in thousand acres)

Crops	1950-1951	1954-1955	1959-1960	Annual average 1950-1951 to 1959-1960
Rice	19 906	21 336	21 151	20 487
Wheat	93	103	137	106
Barley	82	86	64	76
Pulses	1 006	1 115	771	936
Potato	75	121	116	117
Sweet potato	...[1]	...[1]	87	—
Oil seeds	716	446	835	—
Sugar-cane	225	263	280	251
Vegetables	536	550	...[1]	—

1. Figures not available.

Sources: Agricultural and Animal Resources of East Pakistan, 1961; *Land and Crops Statistics of Pakistan*, 1959.

While the acreage under the main food crop, rice, has shown an upward trend from 19.9 million acres in 1950-1951 to 21.1 million acres in 1959-1960, production of rice has fluctuated. Taking 1947-1948 as the base year, rice production varied between 100 and 113 during 1941-1945 and 1952-1953; between 94 and 125 during 1953-1954 and 1959-1960; and between 129 and 141 during 1960-1961 and 1962-1963.[3] The fluctuations have

1. The other factor influencing double cropping is the crop grown during the rainy season. *Aman* rice, which accounts for more than half of the gross cultivated area, is generally grown on one-cropped lands, whereas jute and *aus* paddy, which are usually grown on higher levels, form a substantial percentage of the crops on double-cropped land.
2. For a comprehensive account of cropping patterns and population densities, see Nafis Ahmed, op. cit.
3. *Economic Survey of East Pakistan*, Dacca, 1963, Table 2, p. 2. Production of rice in the base year was 6.75 million tons.

been due mainly to natural calamities like floods, drought and cyclones. In 1962-1963 floods caused a loss of more than 1.2 million tons of rice.[1] Prior to 1955-1956 the over-all production of food grains by far and large was sufficient to meet the food requirements of the province. Shortages were mostly periodical, necessitating small imports. From 1956 onwards food production started lagging behind the increasing demands for food due to the rapid increase of population (see Table 7).

TABLE 7. Supply position of rice in East Pakistan, 1955-1956 to 1962-1963 (in million tons)

Year	Total requirements of the province[1]	Production of province	Supply available[2]
1955-1956	7.57	6.38	5.79
1956-1957	7.72	8.19	7.73
1957-1958	7.86	7.60	7.08
1958-1959	8.01	6.92	6.05
1959-1960	8.15	8.48	8.11
1960-1961	8.30	9.52	8.11
1961-1962	8.45	9.47	8.72
1962-1963	8.50	8.72	7.50[3]

1. Estimated at the rate of 18 oz. per day for effective adult population which is estimated at 89 per cent of total population.
2. Total supply equals production, minus seed, feed and waste estimated at one-ninth of production (according to Planning Commission) minus internal procurement plus government distribution.
3. Approximate.

Source: Economic Survey of East Pakistan, 1963, op. cit., Table 9, p. 9.

The increasing shortage in the supply of food grains has necessitated large imports from West Pakistan and abroad (see Table 8).

TABLE 8. Import of food grains from West Pakistan and abroad (in thousand tons)

Year	Rice	Wheat (including flour)	Year	Rice	Wheat (including flour)
1956	533.2	51.4	1960	401.7	176.1
1957	432.1	75.3	1961	356.8	187.4
1958	465.8	135.5	1962	270.5	534.2
1959	422.7	161.0			

Source: Economic Survey of East Pakistan, 1962-1963, Table 10, p. 50.

The imports of rice show a progressive decline from 533,200 tons in 1956 to 270,500 tons in 1963, whereas wheat and wheat flour have increased by 100 per cent from 51,400 tons in 1956 to 534,000 tons in 1962. This decline in rice imports and increase in wheat imports reflect the changes in the dietary habits, though slow, that are taking place in East Pakistan due to a constant food shortage, which in East Pakistan means a rice shortage. In addition to these food grains the province also has to import pulses, oil seeds (including edible oils) and sugar as the production is insufficient to meet the requirements of the province. During the period 1955-1956 to 1959-1960 the annual import of pulses (gram) varied between 10,000 and 15,000 tons, that of oil seeds between 100,000 and 125,000 tons and that of sugar by about 20,000 tons.[2]

The rapid increase of population is bound to further aggravate the food shortage in the years to come and imports of food grains may increase to such an extent that the province may even find it difficult to meet her other requirements for consumer and capital goods. The economic development, particularly industrialization, of the province may therefore be considerably retarded because of increasing imports of food grains due to a rapidly expanding population.

East Pakistan's economic future, therefore, largely depends upon the solution of her population problem. Possibilities of emigration are almost non-existent and the solution of the problem lies in reducing the birth rate and also in increasing food production. The widespread introduction of positive checks on the growth of population is, however, not an easy task. At present it is at the most an urban idea and will take a long time to spread to the rural areas. A fall in the birth rate, though highly desirable, cannot be expected in the near future. Meanwhile population will continue to increase, in view of its age structure and declining mortality. The problem of increasing food shortages will become more acute and it will be necessary to increase food grain production if disaster is to be averted.

Food grain production can be increased partly by increasing the cultivated area and partly by raising the output per acre. East Pakistan has about 22 million acres of cultivated land, of which about 1.5 million acres are fallow. There are about 4 million acres of land classed as cultivable waste and the possibility of reclaiming this land is not promising as it represents mostly marginal or ill-drained land. The area under double cropping is about 6 to 7 million acres and it may be possible to increase the double-cropped area by providing irrigation facilities during the dry season and by introducing earlier ripening varieties so as to allow a second crop to be sown while the soil is still moist. Increase in the double-cropped area would help to increase agricultural production and would thus relieve to some extent the food shortage.

Increase in yield, however, is the best hope. Yields of all food grains are very low and the yield per acre of the principal food crop, rice, is amongst the lowest in the world. Rice yields vary between 800 lb. and 1,000 lb. per acre depending upon weather conditions during the growing stage. The rice yield in East Pakistan is between one-third and one-half of the yield in Japan or China and can be increased substantially. This will require improvements in agricul-

1. *Economic Survey of East Pakistan*, 1963, op. cit.

2. *Agricultural and Animal Resources of East Pakistan*, 1961, p. 17. 44 and 53.

tural techniques, application of fertilizers to the depleted soils which have been producing crops year after year with little manuring, improved quality seeds and plant protection measures.[1] "Time, however, is a factor to be considered, as the rate of improvements would probably be slower than the demand for greater food supplies. Further, the established habits and prejudices of the people may make many of the obvious remedies impracticable" (Baker, 1936, p. 235).

1. In the Second Five Year Plan (1960-1965) it is proposed to increase food grain production by 1.37 million tons by 1964-1965; 33 per cent of the increase is to be obtained by application of fertilizers, 23 per cent by plant protection measures, 17 per cent by improved seeds, 14 per cent by better drainage, 8 per cent by cultivating new areas and 5 per cent by better cultural practices. See *The Second Five Year Plan (1960-65)*, Karachi, 1960, p. 142.

Résumé

La population du Pakistan-Oriental (A. M. Patel)

Le Pakistan-Oriental, avec une superficie d'environ 143 000 kilomètres carrés et une population de 50 millions d'habitants (1961), est l'une des régions les plus peuplées de la zone tropicale humide. L'accroissement rapide de cette population, essentiellement rurale, met à rude épreuve l'économie du Pakistan-Oriental, fondée sur l'agriculture.

Cette population a doublé en quatre-vingts ans, et son accroissement s'est accéléré au cours des trente dernières années. Le taux d'accroissement accuse une tendance ascendante : entre 1951 et 1961, il était de 2,1 % par an. Comparé à ceux d'autres pays, ce chiffre n'est pas élevé; mais il se traduit par une très forte augmentation en valeur absolue : 8 millions en dix ans (1951-1961). Il est difficile d'avoir des données sûres au sujet des naissances et des décès car les chiffres officiels ne tiennent pas compte des naissances et décès non enregistrés. Les taux probables de natalité et de mortalité semblent être respectivement de 44-46 et 21-23 pour mille habitants. L'accroissement démographique est dû pour une large part à l'accroissement naturel. Le taux de natalité est resté presque constant tandis que le taux de mortalité n'a cessé de décroître, principalement grâce aux mesures de santé publique et à l'absence de famines.

La répartition de la population par âge donne une pyramide à large base se rétrécissant rapidement vers le haut; cette population continuera donc à augmenter, pendant quelque temps encore au moins. La répartition par sexe accuse un excédent d'hommes par rapport aux femmes (105 à 110 hommes pour 100 femmes); mais, dans le groupe d'âge de zéro à quatre ans, les filles prédominent. La population est rurale à 95 % environ, bien que le pourcentage de population urbaine ait légèrement augmenté depuis dix ans. En 1961, les centres urbains les plus importants étaient Dacca (556 710 habitants), Chittagong (364 305 habitants), Narayanganj (162 054 habitants) et Khulna (127 970 habitants); ces quatre villes représentent un peu plus de la moitié de la population urbaine totale de la province. Leur croissance actuelle est due pour une large part au développement de leur activité commerciale et industrielle.

En 1961, la densité moyenne de la population de la province était de 350 habitants au kilomètre carré. Cette population est inégalement répartie : elle est très dense au centre et à l'est, plus clairsemée à l'ouest, au sud et au sud-est. Les régions les plus peuplées sont celles qui avoisinent les fleuves, en particulier les terres riveraines de la Padma inférieure (Gange) et de la Meghna, où les densités se situent entre 570 et 770 habitants au kilomètre carré et dépassent même parfois ces chiffres. La densité de la population du Pakistan-Oriental est, dans une large mesure, le résultat des conditions géographiques : il semble qu'il y ait une relation directe entre la capacité de production agricole du pays et la densité de la population. Malheureusement, la production des céréales n'a pas augmenté au même rythme que la population et, depuis 1956, il a fallu recourir à des importations pour compléter la production locale. Au rythme actuel, il semble que les importations atteindront bientôt un million de tonnes par an. Ces importations considérables de céréales nuisent au développement économique de la province et l'augmentation continue de la population ne fait qu'aggraver la situation. Une diminution du taux de natalité s'impose donc, mais, étant donné l'importance de la population rurale illettrée, l'application de mesures positives de limitation des naissances n'est pas près de se généraliser ou de porter ses fruits. Il faut donc se préoccuper immédiatement d'augmenter la production de céréales si l'on veut éviter la catastrophe. Comme il n'est pas possible d'accroître la superficie des terres cultivées, le seul remède semble être l'augmentation des rendements. Ceux-ci sont très faibles pour toutes les cultures, en particulier pour le riz, qui est la principale denrée alimentaire; on pourrait donc, en prenant les mesures voulues, augmenter les rendements de façon appréciable. Mais il importe de le faire le plus tôt possible, avant que le problème démographique devienne insoluble.

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Need for land-use studies in East Pakistan

N. Ahmad and F. Khan

Land is needed for food, shelter, work, recreation, movement and security. With the growth of population and developing complexity of man's requirements, the need for land is increasing. But land is not an inexhaustible commodity. Therefore, judicious and balanced use of it is essential. Apportionment of land to rival claimants must be made with great care. This is particularly true of an area like East Pakistan where the density of population is high (922 persons per sq. mile) and the rate of population increase is also high.

East Pakistan has an area of 55,126 sq. miles (i.e., over 35 million acres) and had a population of over 50 million in 1961. In other words, *per capita* there is only 0.7 acre of land. It is from this small proportion of land that food has to be produced; a portion has also to be allocated for the family house and for the school, place of worship, hospital and other communal uses. Industries, roads, railways, etc., also have claim on this limited land. This shows the amount of care needed in determining the use of it. But before future planning is undertaken, the present land use should be carefully understood. The urgency of the matter can be better appreciated if some aspects of present land use in East Pakistan are presented.

AGRICULTURE

Agriculture is the main resource of the people of East Pakistan. Dependence on agriculture has increased in the course of recent years, from 1951 to 1961. In 1951, 83.1 per cent of the civilian labour force was engaged in agriculture; this percentage increased to 85.3 in 1961.[1] The agricultural labour force increased but, unfortunately, the net cropped area decreased from 22.0 million acres in 1947-1948 to 19.1 million acres in 1960.[2]

1. *Census of Pakistan*, 1951, Vol. 8, Table 1, p. 1-3; *Population Census of Pakistan*, 1961, Economic Characteristics; *Census Bulletin*, No. 5, Statement 3, p. vii.
2. *Season and Crop Report of East Bengal for the Year 1947-48*, Directorate of Agriculture, Government of East Bengal, 1954, p. 5; and *Pakistan Census of Agriculture*, Vol. I, p. 108 and 114.

It is interesting to note that this decrease was recorded after 2.3 million acres of arable waste land had been reclaimed and put under the plough. In other words, in the course of the 12 years from 1948 to 1960, 5.2 million acres, that is 23 per cent of the net cropped area, have been given over to non-agricultural uses. It is an alarming situation for an area where agriculture forms the backbone of the economy and where dependence on agriculture is increasing.

It is still more alarming to note that not only are the agricultural lands being lost but the best agricultural lands are being swallowed up by the growing towns, expanding industries, new roads and other non-agricultural uses. This is evident from the fact that the towns, industries, roads and other similar claimants of land prefer to occupy non-flooded areas because large amounts of money would have to be spent on filling and raising other land above the flood level. It is again interesting to note that the best agricultural lands in East Pakistan are those which either are not at all or only slightly flooded. The land-use studies recently conducted by us in the Rampal Union and the Faydabad area bring out clearly that all the double and triple-cropped areas are either non-flooded or slightly flooded, whereas the deeply flooded areas are single-cropped areas (Anon., 1961*a*; Ahmad and Khan, 1961). This cropping pattern is likely to be further extended with the increase in irrigational facilities. In the deeply flooded areas, the flood-water comes earliest and recedes last. Consequently in some areas only a few months during the dry season are available for crop production (December to March) and *boro* rice (post-flood) is grown. Sowing of the floating variety of *aman* rice is effected in some areas before the arrival of the flood-water in February-March and the crop is harvested in December. The result is that only one crop can be grown in such areas. In non-flooded or slightly flooded areas on the other hand, both the rainy and dry seasons can be utilized for growing two different crops and if crops with short growing seasons are planted more than two crops can also be produced.

The loss of 23 per cent of agricultural land in a period of 12 years, from 1948 to 1960, creates a serious situation, particularly when it is found that 96 per cent of the arable area has already been brought under the plough, and that only 4 per cent of the marginal lands can be termed as cultivable waste.[1] The only redeeming feature is that the acreage of land cultivated more than once has considerably increased during the same period, from 3 million acres in 1948 to 8.8 million acres in 1960. With better irrigational facilities, greater application of manures and fertilizers and introduction of crops with a shorter growing season, the total cropped area can be further extended by double and multiple cropping. But with low agricultural yields and high rate of population growth, there is no scope for complacency. The available agricultural lands must be jealously guarded and should only be given over to other uses when inevitable. It must, however, be admitted that the large part of land for houses, industries, roads, etc., will have to be contributed by the agricultural lands since the waste lands are almost negligible in East Pakistan and the areas occupied by forests (being already inadequate: 15.8 per cent of the total land) and large water bodies (rivers, lakes, etc.) cannot be given over to other uses.

SETTLEMENT

In East Pakistan there were, in 1961, 78 towns and over 60,000 villages. About 5.2 per cent of the total population lives in towns and 94.8 per cent in the villages.

In the towns of East Pakistan, the number of houses per acre is found to be 2.3. This figure is not quite realistic, because large areas within the town limits are crop land. According to a study made in Comilla Town about 25 per cent of the land was under crops (Khan and Masood, 1962). If this is taken as the average amount of land under crops in other towns of East Pakistan, the number of houses per acre will be 3.1. For towns in East Pakistan, it has been estimated by the Town Planning Department of the Government of East Pakistan that 50 per cent of the land is needed for net residential areas. This compares favourably with the British towns where about 43.5 per cent is needed for housing alone (Wibberley, 1962, p. 47). On this basis the housing density becomes 6.2 per acre. It has been estimated that 10 houses per acre (4,840 sq. yd.) give a sufficiently large plot for a fairly large house with a small garden (Stamp, 1960, p. 72-73). But due to the scarcity of land 18 houses to an acre are being recommended in Britain and also multi-storey flats are being built. This clearly demonstrates that in land-hungry East Pakistan the town-dwellers are rather extravagant in the use of land. It is necessary that the housing densities be increased and that urban spread in agricultural lands should be checked as far as possible. But it is interesting to note that new housing estates, outside the municipal limits in many cases, are springing up in 16 towns of East Pakistan. Nucleus houses of 144 sq. yd. each are being constructed in most of the housing estates and house plots varying in size from 200 to 2,400 sq. yd. are being laid out. The average size of plots works out to be 500 sq. yd. This is a large size even according to European standards. It must, however, be added that the average housing density does not reveal the correct situation in all parts of the town. In certain areas within the town, the housing density rises to 50 per acre and subhuman living conditions prevail.

The conditions in the rural areas are similar to those in towns. The land-use survey of the Rampal and Faydabad area reveals that the average size of houses is 0.2 acre. Thus the housing density per acre is 5, which is worse than in the town areas. To this it must be added that in rural areas part of the house is usually devoted to vegetable growing, and that many of the farm operations like threshing, winnowing, etc., are done at home. Thus a larger area for the house is required. Still it is felt strongly that after going thoroughly into the question of space requirements for rural houses, a maximum area for each house should be prescribed because otherwise, in addition to 1.8 million acres occupied by houses, 0.3 million acres more will be required by 1971 for construction of houses alone, provided the population growth rate is the same as between 1951 and 1961 and the family size (5.4) remains the same as in 1961.

INDUSTRIES

A marked industrial growth has recently taken place in East Pakistan. The income from manufacturing industries was doubled from 1949-1950 to 1959-1960 (from 587 million to 1,072 million rupees). This was made possible by establishing many new industries. Khulna, Chittagong and Narayanganj in particular have expanded because of industrial development. Chittagong has expanded by 47 sq. miles beyond the municipal limits. The industrial area in Khulna has an area of more than 7 sq. miles, and that of Narayanganj 4.75 sq. miles. Again industrial estates have been laid out in a number of other towns of East Pakistan and many more will come up with the expanding economy. That means more land will have to be allocated for the growing industries. It is preferable to allocate uncultivable land for manufacturing plants but the industries, locational factors and the development cost of land have to be ascertained before land allocation can be made. At the present moment we neither know the total area of land occupied by industries nor do we have any estimate of future requirements. It is essential that an industrial land-use survey be conducted with a view to finding out how the industries use and misuse the land.

1. *Pakistan Census of Agriculture*, 1960, Vol. I, p. 108-114.

TRANSPORT

The development of transport systems is closely linked with the economic development of the area. In East Pakistan a comprehensive plan for the development of roads, railways, water and air transport has been outlined (Anon., 1961*b*). This includes improvement of existing transport systems and construction of new roads, railways, river and seaports and airports. It is estimated that 5,600 million rupees ($1,133 million) will be spent by 1980. Financial problems have been fully discussed in the plan. The number of passengers and tonnage of goods likely to be handled have been estimated. Organizational aspects have also been discussed, but no estimate has been made of the land required for these developments. Usually the planners take for granted that the land is available and can be acquired when and where required.

In like manner land is required for recreation, irrigation, power development, defence services and other uses. Land being a scarce commodity in East Pakistan, no extravagance can be permitted. We should have a Land Planning Department which should be empowered to allocate land for various purposes, as we do with the allocation of funds. Funds can be made available by taking loans from other countries or international agencies but additional land cannot be obtained from anywhere. For a judicious allocation of land a comprehensive and not a piecemeal planning is necessary. Again no planning is possible without knowing the present land use. Therefore, a land-use survey of East Pakistan is urgently required as has been made in other parts of the world.

The urgency of a land-use survey has been fully recognized by the International Geographical Union which set up a Commission on World Land Use in 1949. Its objective was to initiate land-use studies on a world-wide basis.

On the lines suggested by the *IGU World Land Use Survey*, the Department of Geography of the University of Dacca undertook the first land-use study of a village (Majhina Nadirpar) in East Pakistan and results of the survey were published in the *Pakistan Geographical Review (Lahore)* (Ahmad and Khan, 1957). This was followed by a pilot project on land use in the Rampal Union (Dacca district), which was later published as Monograph No. 1 of the East Pakistan Geographical Society (Anon., 1961*a*). Recently, Monograph No. 2 of the East Pakistan Geographical Society has been brought out with the help and financial assistance of the Social Science Research Committee of Dacca University (Ahmad and Khan, 1963). A number of other villages have been studied from time to time and the reports on some of them have been published in the *Oriental Geographer* and the *Pakistan Geographical Review* (Naqavi, 1957, 1959; Khan, 1957; Haque, 1958; Islam, 1959; Khan and Haque, 1961). The Department of Geography of the University of Rajshahi has also developed land-use studies.[1] It produced such a study on land use in Puthia Union, conducted in collaboration with the Socio-economic Board of the University of Rajshahi. The village Academy Comilla has also undertaken some land-use studies in recent years (Quadir, 1960).

But all these studies cover only a small fraction of the area of East Pakistan. A comprehensive land-use study of the whole province is urgently needed. This can only be done if the government or some other agency initiates such work and provides adequate funds. When such surveys are undertaken, aerial photographs will have to be combined with ground-checking and field-work.

1. *Preliminary Report of Land Utilisation and Education Survey of Puthia Union, Socio-economic Survey Project, Rajshahi University* (Mimeographed); Ahmed M. Patel, "Dausmari Village. A Study in Land Use", *The Oriental Geographer*, Vol. V, No. 2, July 1961, p. 121-136.

Résumé

De la nécessité de faire une étude sur l'utilisation des terres au Pakistan-Oriental (N. Ahmad et F. Khan).

Les auteurs font ressortir qu'en raison du chiffre grandissant de la population et de l'accroissement de ses besoins, les terres cultivables deviennent de plus en plus rares. Elles n'en sont pas moins nécessaires à l'économie du pays et l'utilisation judicieuse des terres est un facteur essentiel à son développement. Il est alarmant de constater que même les meilleures terres sont perdues pour l'agriculture car elles sont avalées par les agglomérations urbaines en voie d'expansion et utilisées à des fins non agricoles telles que routes, usines, etc. Les auteurs font un exposé des études partielles qui ont été faites mais insistent sur la nécessité de procéder à une vaste étude d'ensemble pour l'utilisation des terres de tout le pays.

Discussion

D. MUELLER-DOMBOIS. I wonder why natural vegetation was not considered in this otherwise rather complete land-use survey.

H. BOESCH. The interest of the survey was merely in establishing current use patterns in relation to the land.

NAFIS AHMAD. Even a survey of current distribution patterns could usefully include that of natural vegetation.[1] Furthermore, an orientation by basic distribution patterns as given by geological, surface-relief and soil features, currently cultivated crops, etc., should be followed up by an evalution of the land in terms of its physiological potential as this appears to be the ultimate purpose of a land-use classification. A knowledge of natural vegetation is indispensable for estimating the physiological potential of different land segments. Thus, natural vegetation should enter into land classification in two ways: (a) as one of the distribution patterns; (b) as a primary source of information about the physiological potential of the land.

1. *Author's note:* "Natural vegetation" here is understood as that kind of unmanaged vegetation that reflects by its composition and structure a significant adaptation to local environments or, negatively defined, unmanaged vegetation whose composition and structure is not dominantly influenced by recent disturbances.

F. R. FOSBERG. My understanding of this paper is that it involves land-use studies, not simply a map showing present-day use of the land, which may be so temporary that the map will be obsolete before it is printed. Such land-use maps are only the first step in the kind of studies that Dr. Khan has been discussing. These involve the relation between the tremendous population of Pakistan and the limited land available. In my opinion, the vegetation study suggested by Dr. Mueller-Dombois is useful in determining the potential of the land, thus enabling better judgement as to the best land use.

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Influence of flood-protection works on physical and biological environment

P. Santema

INTRODUCTION

In other contributions to this symposium descriptions have been given of the geomorphological and hydrological conditions prevailing in deltas in their original natural state. From these descriptions it follows that flooding always forms an essential feature of these conditions. It goes without saying that the physical environment in such natural deltas is not always and in every respect favourable with regard to the living conditions in general and man's economic activities in particular. Whereas on the one hand man has been active since the earliest times to improve the physical environment, by means of flood protection works among other ways, on the other hand a certain adaptation to the unfavourable circumstances has taken place, in such a way that the people inhabiting the deltaic areas have learned how to live with the floods.

From the above-mentioned other contributions it follows that a delta in its natural state features a never-ending geomorphological adaptation to the continuous process of delta building and to the varying geological and hydrological influences. Introduction of artificial elements, such as flood protection works, interferes with this natural adaptation and has repercussions, not only for the directly affected hydrological phenomena, but also for the geomorphological, pedological and biological processes taking place in the delta.

In the following paragraphs, first, a few more general aspects of the introduction of flood-protection works in deltas will be discussed. Next, the various means of flood protection and the results which may be obtained thereby will be dealt with; the effect of their interference with the geomorphological processes of adaptation in naturally developing deltas will be mentioned also. For this more detailed discussion the subdivision of deltas mentioned in my previous contribution (p. 109) will be followed here, viz.; (a) lower part where the effect of the sea level predominates; (b) upper part where the effect of the river floods predominates; (c) intermediate zone where a combined effect of sea and river floods occurs.

The symposium being held in Dacca (East Pakistan), most of the examples mentioned for elucidation of phenomena described relate to deltas in South-East Asia.

GENERAL DISCUSSION

For a better understanding of the influence of flood control works on the physical and biological environment it may be useful to mention first a few aspects of the adaptation of man's activities to the prevailing unfavourable natural conditions in the humid tropical zone deltas.

The adaptation of agriculture to the natural conditions of flooding is most remarkable. The crop which offers the best possibilities under the climatological, hydrological and pedological conditions prevailing in the deltas of the humid tropical zone is rice, which consequently is by far the major crop in these areas. The various methods of rice growing which are in use in the deltas of South-East Asia very clearly demonstrate the extent to which an adaptation of agricultural practice to the natural conditions of flooding is possible.

Floating rice may be grown in those parts of the deltas where inundation penetrates very deeply and the rate of the water level's rise is great. After the first rains the seed is broadcast and later the farmers leave the area for the higher lands. Before the floodwater starts to rise the stems should have reached a length of 0.5 to 1.0 metre; the plant is then able to grow with the rise of the water level at a maximum rate of about 10 cm. per day, thus withstanding inundations reaching a maximum of 3 to 4 metres (even 5 metres under favourable conditions). Semi-floating rice has similar characteristics, but may be replanted; the maximum inundation which can be withstood is about 1.5 metres. Long-stemmed rice has characteristics

similar to those of normal rice, but grows somewhat faster. In parts of the delta where the circumstances of flooding prohibit even the growing of floating rice, rice may be grown on the fringes of such areas during the rivers' falling stages or over larger areas during the dry season. On the moderately inundated soils "very early", "early", "half-season", "season" or "late" rice may be grown (distinction is made according to the time of sowing in the wet season; a broader distinction according to the time of harvest is made between autumn and winter rice). The type of cultivation to be chosen, with its specific time of sowing, replanting and harvest, depends very much on the nature, depth and time of flooding. In some parts of the deltas the natural conditions may be such that two rice crops can be grown; normally some kind of water control is then necessary.

On the more elevated soils of the delta sometimes other crops are also grown, e.g., in the wet season: jute, cotton, maize, millet, sugar-cane, vegetables; and in the dry season: wheat, barley, grams and beans, oil seeds and groundnuts, potatoes, tobacco, vegetables.

Although a remarkable adaptation of the agricultural practice to the prevailing natural conditions has taken place, the over-all agricultural production per unit area is generally low (except in countries like Japan and Taiwan). To increase the agricultural production various steps must be taken including: improvement of agricultural techniques (such as applying fertilizers and manures, seed selection, weed control, pesticides, etc.); diversification of crops with crop rotation and multi-cropping; land consolidation and mechanization. For several of these steps it is necessary to improve considerably the existing water control system.

When planning further development of deltaic areas it is important to decide to what extent improvement of the existing water control is desirable and feasible.

Adequate water control means that the beginning, duration and depth of flooding (or successive floodings) of the farmers' fields are controlled. This normally involves the introduction of flood protection, drainage and irrigation facilities. The flooding is caused not only by the river floods and the tidal floods, but also by local rain.

A more or less complete protection against river and sea floods would be meaningless if excessive flooding by local rain still occurred. Flood protection and drainage, therefore, should nearly always be considered jointly. Assuming a more or less complete protection against river and sea floods, the available or economically feasible drainage facilities in humid tropical zone deltas are generally not sufficient for water control to the extent of growing "dry" crops in the wet season. (Thus for the coastal embankment project in East Pakistan a drainage criterion of 25 mm./day has been assessed for areas with an annual rainfall of 1,750 mm., assuming that a storage of 150 mm. water on the fields is permissible.) Under such circumstances attention remains focused on crops which can be grown under more or less waterlogged conditions in the wet season, such as rice. In several cases, therefore, flood regulation, instead of complete protection against floods, may already give very satisfactory results because extremes and the consequent risks for agriculture can be avoided.

There may be reasons for which a complete exclusion of flood-water is not everywhere necessary or desirable in a delta. Large parts of the soils of the humid tropical zone deltas (Plaine des Joncs in southern Viet-Nam, Rangsit area in Thailand) consist of so-called "cat-clays" or acid-sulphate clays. The essential characteristic of these soils is a high content of polysulphides. Penetration of air in such soils causes oxydation of the polysulphides resulting in the formation of sulphuric acid which liberates huge masses of soluble highly toxic alum salts from the clay minerals. Under natural conditions only the very top soil is from time to time penetrated by air. There the polysulphide content has been oxydized in the course of many centuries and the oxydation products have been leached. Improved drainage, resulting in a lowering of the water table, would lead to oxydation of the soil ultimately resulting in the formation of new toxic salts. Intensifying this process in order to remove all polysulphides is practically impossible, because it would require enormous quantities of water and last for centuries; the same holds normally for using lime to neutralize the acid. Therefore, the policy should be to prevent new acid formation and to leach out the toxic salts that are present. Leaching requires drainage; strong drainage, however, involves oxydation and thus acid formation. So, moderate drainage to remove the toxic salts, but keeping the area wet almost throughout the year, may give satisfactory results. Cultivation of two rice crops a year seems to be the practical solution but it requires irrigation during the dry season.

Introducing flood control works in a delta results in the decrease of flood-waters entering large areas of the delta, or even in complete exclusion of the flood-waters. This means that these parts no longer—or at least to a much smaller extent—take part in the process of delta-building siltation. Assuming that the flood-control works and the channels across the delta have been so designed that most of the sediment of the river is transported to the sea, building-up the delta into the sea will thus be increased—sometimes considerably—depending on the configuration of the sea bed and the character and strength of the littoral processes of sediment transport in the coastal waters. In several of the deltas in South-East Asia the coastal advance into the sea is considerable (in northern Viet-Nam, in the delta of the Red River, some parts of the coast advance about 100 metres per year). The increased rate of the delta's build-up into the sea means that the flood levels, especially in the intermediate zone of the delta, will be raised at an increased rate; it goes without saying that these flood levels are affected consider-

ably and directly by the introduction of flood control by means of embankments which will confine the volume of flood-water to much smaller areas. The increased rate of building up the delta into the sea causes also an accelerated decrease of river slopes in the delta resulting in sedimentation and raising of the river beds. This is another phenomenon than that of the possible raising of river beds directly due to the introduction of flood control by means of embankments, which normally can be avoided by an adequate hydraulic design of the river bed with its embankments and river training works. The above-mentioned considerations lead to the conclusion that especially the growing intermediate zone of a delta may ultimately be placed in a less favourable position, in a geomorphological and hydrological sense, by the introduction of flood control works. This does not necessarily present unsurmountable difficulties, however. By adequate integral river basin planning characteristics of the main river régime can generally be modified to such an extent that the above-mentioned effects are more than compensated, whereas by the application of modern techniques the increased requirements regarding flood control, technically speaking, can practically always be met. These steps, however, should be justified by the intensification of agriculture and the over-all economic development of the delta made possible by the improved water control.

In this connexion it may be noted that provision of facilities for irrigation and drainage, for power and water supply, for systems of roads, railways and waterways, for sites for ports and industries, etc., can hardly be possible in deltas without the provision of adequate flood control.

It is important that the planning of further development of deltas and particularly of improved water control are carried out within the framework of a master plan for the whole river basin.

In various deltas great value is attached to the fertilizing effect of fresh silt deposited on the fields. Moreover, if the concentration of Ca ions in the silt and the flood-water is high, annual flooding may prevent the soil from becoming acid. Therefore, in various deltas in South-East Asia, controlled inlet of silt-laden flood-water often forms a part of the flood-regulation or flood-control scheme (delta of the Red River in northern Viet-Nam). In some cases, however, the onset of local rainfall comes well in advance of the commencement of the flood with the result that in certain areas the rain water is backed up by the flood-water of the river, so that those parts under natural conditions do not receive much silt either (Irrawaddy delta in Burma). Under such conditions the previously mentioned effect of introducing flood-control works in deltas on the rate at which they build up into the sea will also be less pronounced.

The natural flooding of the land in a delta by fresh water from the river is often beneficial, preventing contamination and pollution of the surface waters and soil salinization. The flood-water flushes the various channels and creeks, removing stagnant water and carrying waste products to the sea. The salts accumulated in the surface waters during the previous dry period are removed and a certain desalinization of the soils can take place. Thus, flooding with fresh water is of importance to maintain good hygienic conditions. There are various examples of deltaic areas where, in the absence of cleansing fresh water, the malaria mosquito thrives.

Flood-protecting embankments have a considerable influence on this aspect of the physical and biological environment. However, any adverse effect of flood protection can be eliminated by an adequate system of drainage. In this connexion provision of outlets in the embankments is not sufficient. A system of ditches and canals to carry the excess water to the outlets is equally important. In this way the drainage of rain water can have a flushing effect and in some cases provision for additional flushing will be necessary.

FLOOD PROTECTION IN THE LOWER PART OF THE DELTA

Several deltas in the humid tropical zone are affected in their seaward parts by the normal tidal movement only; rises in the sea level, caused by storm surges, etc., are small and/or occur very seldom in those cases. The usual type of flood-protection work is the coastal embankment which rises only moderately above the level of normal spring tides. In fact such embankments serve more the purpose of preventing salt-water intrusion than of flood protection in the proper sense of the word. Sometimes various reaches of the coastal embankment are connected by dams across tidal creeks or estuaries, possibly provided with sluice gates or movable weirs; the latter structures serve local drainage purposes or are used to evacuate flood-water from the rivers.

More common is the case of the water levels being affected by rises in the sea level. Depending on the cause and the consequent type of rise in the deep sea, the configuration of the sea bed in the coastal zone and the configuration of the estuarine part of the delta, the raising of the sea bed may be considerable. A rise of the sea level is, moreover, usually accompanied by strong-wind waves in the coastal waters. In order to minimize the impact of these waves on the coastal embankment, a sufficiently broad strip of foreland is preferably maintained between the dike and the sea. Even better results are obtained with a protective belt of mangrove forest left in front of the dike. This can be of great practical importance because, in the large deltas of the humid tropical zone, stone for protective revetment of the dikes' outer slope is usually not available and, therefore, would be expensive; other materials such as concrete and asphalt are also expensive.

The design criteria, as far as the sea level and the waves are concerned, largely have to be based on economic considerations. The establishment of extreme values often involves an extrapolation of records from the past. It should be kept in mind, however, that the application of modern scientific methods in the fields of meteorology, oceanography, tectonics, etc., together with modern mathematical and experimental techniques, make it possible to obtain better evaluations of extreme values and—under favourable circumstances—even to make reliable forecasts. The importance of maintaining a well-planned network of observation points and in several cases of an adequate system of telecommunications may be stressed in this connexion. In a number of deltas in South-East Asia and the Far East the design criterium prescribes that embankments should be able to withstand floods with a frequency of occurrence of once in a hundred years. For comparison it may be mentioned that in the deltaic areas of the Netherlands this figure is once in a thousand years for rural areas and once in ten thousand years for the densely populated and heavily industrialized areas.

In the case of reclamation of new tidal land the level of the lowest land which is still considered suitable for reclamation has to be decided. In some deltas the policy has been adopted that only land that has silted up to about the normal high-water level is reclaimed. In other deltas, and notably those with a high population pressure, land of a much lower level has been reclaimed; if drainage is based on gravity flow, a level somewhat higher than normal low water is accepted, and if drainage by pumping is feasible land with an elevation much below normal low water may be considered as suitable for reclamation.

In this connexion it may be mentioned that deltaic lands which have been reclaimed, and are no longer subject to siltation, will gradually become lower with reference to mean sea level due to the shrinkage of the thick layers of deltaic sediments, and this even more if the top layers are drained intensively. Rise of the sea level will increase this relative subsidence; crustal movements may increase it also, or counteract it. Furthermore, the distance between the reclaimed land and the coastline will increase more and more due to the continuous growing of the delta into the sea. By these processes the elevation of the reclaimed land with reference to the normal low-water levels in its neighbourhood may become such that natural drainage will no longer be possible and drainage by pumping will be necessary. This moment will be reached sooner if the level of the land is lower with reference to the low-water level and if the project is located in a very active part of the delta. In such parts the rate of coastal advance due to the delta building up into the sea can be high.

The soil texture of the land to be reclaimed usually depends on the level to which the land has silted up, the heavier soils being usually higher and the more sandy soils lower. Salinization difficulties have been especially encountered with the low-lying soils.

We can conclude that, when planning coastal reclamation projects, not only should the momentary situation be taken into consideration, but also the conditions to be expected in a not too distant future.

Sometimes the sedimentation on tidal forelands is promoted by artificial means in order to accelerate the raising of the land's level and the improvement of soil texture. This may be done by creating favourable conditions for sedimentation and for consolidation of the sediment by promoting growth of suitable vegetation, providing ditches and constructing sedimentation pans with the help of groynes.

The delta's usually very fragmented zone towards the sea normally requires very long embankments for flood protection. In order to shorten this line of defence, a number of tidal creeks and estuaries may be closed. In this connexion it may be noted that there is a certain relation between the number and the dimensions of the tidal inlets on the one hand and the scouring forces of the volumes of water flowing in and out of tidal basins behind the coastline, on the other hand. The scouring forces are important for protecting the entrances against the processes of littoral sediment transport trying to close such inlets. A reduction of the tidal basin by reclamation works on the one hand, and a reduction of the number of tidal inlets on the other hand, affect this equilibrium.

In view of sea navigation it is generally advisable not to close all the tidal openings in the part of the delta facing the sea; to evacuate flood-water from the rivers some of these openings should be left open also, or else the dams therein must be provided with sluice gates or movable weirs. Even by closing only part of all the existing openings a considerable reduction of the highest tidal water levels in the tidal basin behind the coastline may be obtained. An example of this is provided by the well-known Dutch delta scheme.

Another advantage of the closure of a number of openings in the coastline is that salt-water intrusion can be prevented much more efficiently by concentrating the dry-season's flow of fresh water to the sea in a smaller number of openings, so that tidal waters thus closed in can be transformed into freshwater basins. Especially in those parts of deltas which may be classified as non-active—or which are in the non-active phase of a natural cycle, or which are fixed in the non-active phase by large-scale engineering works—the closure of tidal creeks and estuaries may be very effective, because the natural inland advance of salt water may thus be stopped.

The natural drainage of the land around the tidal basin is somewhat adversely affected by the closure of a number of openings along the coastline because, generally, there is a rise of the low-water levels. Compensating measures such as providing canals for direct

drainage into the sea or pumping stations will be required.

The closure of an opening in the coastline also affects littoral processes in the coastal waters. The currents flowing at right angles to the coast are cut off, with the result that the system of gullies and banks before the former opening will gradually become less pronounced and the micro-underwater-delta of the former opening will show a tendency to move towards and along the coastline.

Introducing a scheme by which certain openings will be closed and others left open, generally speaking reduces the currents up and down the delta but enlarges the transverse currents, especially in those deltas where the sea's tidal waves approach the coastlines more or less at right angles, so that there is little or no phase difference between the tidal motion in the left and in the right parts of the deltas. The transverse currents are usually weak and it is difficult to keep the transverse connexions open for navigation. The closure of a number of openings in the coastline may improve such a situation considerably and it is even possible that provisions may have to be made to avoid excessive erosion in the transverse waterways (an example is provided by the Dutch delta project).

It goes without saying that fishing in the tidal waters is affected also by the above-mentioned projects and this is true also for the natural vegetation (mangrove forests, etc.).

Going inland from the coast the following series of natural vegetation is generally found: vegetation on the beach ridges, mangrove forests, normal tidal forests and tropical rain forests. The mangrove stands and the tidal forest are very sensitive as far as mud deposits, normal tidal variation of water levels and salinity are concerned. Generally, if one of these factors varies, a new pattern of natural vegetation will develop.

FLOOD PROTECTION IN THE UPPER PART OF A DELTA

The requirements as to flood protection in the upper part of a delta largely depend on the character of the water régime of the delta-building river at the apex of the delta. In various rivers the water régime is irregular so that the beginning of rise and fall of the water levels and the normal maximum and minimum water levels are extremely variable; the rate of rise and fall of the water levels is great. Such an irregular water régime involves an extremely variable situation as far as flooding is concerned, with consequent great risks for agriculture and normally, under these circumstances, some kind of flood protection has been introduced (as in the delta of the Red River in northern Viet-Nam). A more regular water régime on the other hand means that flood protection is not absolutely necessary for moderate agricultural development (as in the delta of the Mekong in southern Viet-Nam and of the Chao-Phya in Thailand).

The character of the river's water régime at the apex of the delta is determined by the physical characteristics of the drainage basin upstream of the delta and the meteorological conditions prevailing in that area. The same features which lead to an irregular water régime generally also bring about a high flood discharge per unit drainage area. Thus, rather extensive flood-protection works are found in the deltas with a high specific flood discharge, whereas major flood protection works may be absent in deltas with a low specific peak discharge. The régime of the river at the apex of the delta is influenced by engineering works carried out in the drainage basin upstream of the delta. Storage reservoirs, detention basins, watershed management, etc., make the régime more regular, whereas extensive systems of high embankments may have the opposite effect.

Extensive flood-protection works may be found also in deltas which are characterized by the large sediment load of the delta-building river and more specifically a large sediment load of this river per unit of deltaic area. In these cases the character of the régime varies from regular to irregular. Such rivers in their natural state, and if provided with embankments on the occasions of breaches therein, have formed enormous natural levees, whereas the river bed is normally raised considerably above the level of the adjacent land. Flooding in such cases may result in a breach of the natural levees with the result that afterwards the river takes an entirely different course to the sea; moreover, such breaches leading to enormous sedimentation on the farmers' land are real disasters. Embanking in these cases is in fact also a means of controlling the process of delta building. A nearly classical example of this type of river is provided by the Yellow River on the mainland of China which, more than once after a flood disaster, took quite another course.

In the upper part of a delta a pronounced system of natural levees and depressions is generally present. In the very upper part the natural levees often take more or less the form of a gently sloping sediment cone. Even in the flat deltaic plain which slopes very slightly in a longitudinal direction, the differences in level of the land in a transversal direction can thus reach several metres; flooding of the levees is generally not deep. In the depressions, however, inundation is generally deep because the flood-water in this part of the delta has not yet had the opportunity to spread over large areas; especially in the lower zone of the upper part of the delta inundation may be deep.

Flood-protection works in the upper part of a delta may include embankments, flood regulators and diversion dams, and flood retention basins. By embankments the flood-water is confined to the river bed, with the result that the flood levels are raised high above the adjacent land (Red River in northern Viet-Nam). In case of a dike breach there may be great damage.

In some cases it may be necessary to keep the flood levels of an embanked river below a certain level as part of the protection scheme or for drainage purposes; the excess flood-water is then directed to other channels or areas by means of flood regulation or diversion dams and spillways. Some deltas are in a favourable position in which the delta-building river has large natural retention basins (Mekong river in Cambodia with the Great Lake); the efficiency of such basins normally can be increased considerably by relatively simple engineering works. In some cases retention basins are found also in the deltas themselves; generally these areas have relatively low development potentialities (deep inundation, little possibility for improving drainage and irrigation facilities, high concentration of toxic salts in the soil, etc.) and sometimes can be best utilized as areas to which the flood-water is diverted in order to protect other areas which are more promising for development.

In some deltas the situation is such that a distinction can be made between the so-called active and non-active parts of the delta. The non-active parts of the delta are then more or less cut off from the river by a high natural levee or by raised areas, and normally are not flooded by the river water, except during the peak of the floods. The provision of improved drainage and irrigation facilities in such areas may be of greater importance than providing protection against river floods (parts of the Ganges delta in India and East Pakistan).

The geomorphological process of delta building may be affected by the variation of the sea level in relation to the elevation of the land. The adaptation of the delta to this new situation starts from the sea side and gradually moves upstream. In case of a relative rise of the sea level the upper part of the delta will have a somewhat lower level with reference to the state when the adaptation has been completed and the severity of flooding will be somewhat greater than when a new state of dynamic equilibrium has been reached again.

FLOOD PROTECTION IN THE INTERMEDIATE ZONE OF A DELTA

Flooding in the intermediate zone of a delta is caused by the rise of the sea level, river floods and local rainfall. In the dry season the normal tidal movement is generally noticeable in the rivers throughout the intermediate zone; in the lower part the current normally reverses, but in the upper part the current is normally continuously directed towards the sea; in the lower part the water's salinity may be affected by the sea water, but the upper part can be classified as a freshwater tidal reach. In the wet season all these zones shift in a downward direction and during the river floods the land usually is inundated by river water and by local rain water. The depth to which the unprotected land is inundated is considerable in the upper part of the intermediate zone, but decreases in a downstream direction; in the lower part, however, the sea-level rise may be the main cause of the highest water levels. Differences in level between natural levees and depressions exist, but are less pronounced than in the upper part of the delta; generally speaking this relief decreases downstream.

Flood-protection works in the intermediate zone of a delta may include embankments, flood regulators, diversion dams and channels, or short-cuts to the sea. In some deltas with rather regular flood régimes the flood protection consists only of low dikes and a system of canals for a more regular spreading of the flood-water over large areas; such canals, which normally are provided with weirs for flood regulation, for water conservancy and prevention of salt-water intrusion, may also serve irrigation purposes, drainage and inland navigation (deltas of the Chao-Phya and the Mekong). If the rises of the sea level do not play an important part, open or "horse shoe" embankments are sometimes found (delta of the Irrawaddy); however, provisions for the control of salt intrusion are normally necessary at the open lower ends.

The drainage of local rain water from large embanked areas in the intermediate zone often poses a problem. The formation of large drainage units extending towards the lower part of the delta (either the embanked areas themselves or their main drainage canals) or the regulation of the flood level on certain embanked rivers which play an important part in the drainage, may form a solution.

Various aspects of flood protection which have been mentioned for the upper and the lower part of the delta play a part also in the intermediate zone.

Résumé

Influence des ouvrages de défense contre les crues sur le milieu physique et biologique (P. Santema)

D'autres documents présentés à ce colloque indiquent les conditions géomorphologiques et hydrologiques qui existent dans les deltas à l'état de nature. Ces descriptions font apparaître que les inondations constituent toujours un des principaux éléments de ces conditions. Il va sans dire que le milieu physique de ces deltas naturels n'est pas toujours et à tous égards favorable

en ce qui concerne les conditions de vie en général et les activités économiques de l'homme en particulier. Si, d'une part, l'homme s'efforce depuis la plus haute antiquité d'améliorer son milieu naturel, notamment par des ouvrages de défense contre les crues, il s'est d'autre part adapté dans une certaine mesure aux circonstances défavorables, de telle manière que les habitants des régions deltaïques ont appris à supporter les inondations.

Les communications indiquées ci-dessus font apparaître qu'un delta à l'état naturel fournit un exemple d'adaptation géomorphologique perpétuelle à un processus de formation continu et aux diverses influences géologiques et hydrologiques. L'introduction d'éléments artificiels, tels que les ouvrages de défense contre les crues, gêne cette adaptation naturelle et a des répercussions non seulement sur les phénomènes hydrologiques directement affectés, mais aussi sur les processus géomorphologiques, pédologiques et biologiques qui se produisent dans le delta.

Cet article étudie d'abord quelques aspects généraux de l'introduction d'ouvrages de défense contre les crues dans les deltas. Il traite ensuite des divers moyens de défense contre les crues, et des résultats qu'ils permettent d'obtenir, ainsi que des effets qu'ils ont sur des processus géomorphologiques d'adaptation dans les deltas qui se développent naturellement. Pour cette étude détaillée l'auteur suit la subdivision des deltas mentionnée dans sa communication antérieure, p. 109, à savoir : régions inférieures, d'un niveau proche de celui de la mer, qui fait sentir ses effets; régions supérieures, où se font sentir surtout les effets des crues du fleuve; zones intermédiaires, soumises aux effets combinés du niveau de la mer et des crues du fleuve.

Le présent colloque ayant lieu à Dacca (Pakistan-Oriental), les phénomènes étudiés ont surtout été illustrés à l'aide d'exemples empruntés aux deltas de l'Asie du Sud-Est.

Discussion

KANOK PRANICH. I agree with Mr. Santema's tenet that agricultural improvement should be planned hand in hand with water control. He even thinks that if possible it should be experimented and demonstrated before the execution of the project.

Perfect water control in most countries of this region may not be realized in the near future because of the magnitude of the work, colossal cost, and lack of time for agricultural improvement which has to justify the investment cost. Therefore execution in steps is anticipated in most countries.

In such a case I endorse Mr. Santema's statement that each step in the planning should fit in with the master plan. A master plan is necessary before any step of execution should take place.

L. J. TISON. La forêt constitue, en bordure de la mer, sur une grande largeur, un obstacle considérable à l'écoulement des crues : la densité de cette forêt est en effet exceptionnelle. Cet obstacle peut être considéré comme devant subsister sinon toujours, du moins très longtemps.

Dans ces conditions, il peut sembler (bien que cela doive être vérifié par une étude moins superficielle) que les travaux d'endiguement dans la partie cultivée du delta ne doivent pas exercer une très grande influence sur une situation hydraulique qui restera avant tout influencée par la subsistance de la forêt.

P. SANTEMA. The existence of a wide belt of mangrove forests in the tidal zone of a delta undoubtedly influences considerably the hydraulic processes taking place. This effect is very marked in the case of processes with a limited duration, e.g., storm surges, etc. Various hydraulic engineering works in the delta upstream of the mangrove forest belt, however, will permanently modify the hydraulic situation and in these cases the effect of the mangrove forest belt will ultimately be only a prolongation of the processes of adaptation.

The influence of hydraulic improvement works

K. Deguchi

INTRODUCTION

Throughout the history of the human race deltas have been the birth-place of civilization and have since early ages maintained an important place as the centres of policy, economy and industry of their regions. The value of deltas as the very foundation of modern industry will increase even further in the future.

Water from the continent concentrates in the delta rivers, bringing the soil which becomes a flat plain with the characteristic land topography, soil and water particular to deltas. Therefore, hydraulic improvement works in deltas mean that any change in the river's régime caused by man must necessarily also influence the formation of the delta.

Rivers, lakes and coasts of most deltaic regions in the world are constantly undergoing changes brought about either by nature or by man. In highly developed areas, however, most of these are artificial changes; hydraulic works, as described in the following sections of this paper, are being constructed or planned to ensure better use of water and land to serve the needs of mankind.

Such hydraulic works are constructed for either single or multiple purposes. Apart from the original purpose, the results produce various effects, each result bringing about another result. This is due to the fact that the various conditions concerned with delta land and water are so integrated, maintaining a complex and delicate harmony, that when the balance is broken unexpected and often adverse new phenomena occur. If the hydraulic works are planned in perfect harmony with the natural conditions of the delta then the result will bring out the development of dormant resources and contribute to the maximum utilization of the delta.

Continuous efforts have been devoted by ECAFE to utilization and development of deltaic areas, and various problems discussed in this paper represent small fractions of these efforts. The author has been engaged in the study of reclamation and utilization of the deltaic areas in Japan and has participated in field surveys of several deltaic areas and in the regional symposia of the ECAFE region. The following discussions are based upon the above-mentioned experiences.

TURNING BRACKISH WATER INTO A FRESHWATER BASIN

This subject is considered one of the most significant works of hydraulic improvement in deltaic areas, outstanding examples of which can be seen in the Zuider Zee project and delta project of the Netherlands and, although on a much smaller scale, in the Kojima Bay project in Japan, where a number of other similar projects have been completed or are being carried out. In many deltaic and coastal areas of the world, there are great possibilities for development of such work.

Most of the delta coastal areas are subject to extremely unfavourable natural conditions, i.e., the concentration, during a certain season, of a very large volume of flood discharge, the control of which is very difficult. Since the high flood lasts only for a short period the delta is mostly influenced by tidal water. In such areas marshes or lagoons retard the discharge of river flood, forming natural freshwater reservoirs. To artificially convert the tidal-water basins into freshwater basins is very useful in solving the problems of control and utilization of water in coastal areas. At the same time these works are protective measures against storms and floods and can control salinization damage. Freshwater basins are made by closing an estuary, inlet, tidal creek or bay at or near the mouth by constructing dikes with sluices. The saline water in the new basin is finally changed into fresh water through repeated desalting of the water by the stream and successive discharge of water from the sluices. The salinity of an artificial lake thus created can be reduced to 300 mg. cl./l. or less, which can fully meet the water requirements of agriculture and industry in quality as well as in quantity. Then, as a result of the artificial

control of the water level in the basin—and because changes are very slight as compared to the tidal range prior to closing these channels—drainage from surrounding land is more favourable than in the case of natural high water. However, there is one case where, on the contrary, it shows more disadvantages than low water. As a result of this, even at a place where drainage was possible by gravity before, it is now necessary to replace the sluices by pumps. As for irrigation a similar influence occurs and it is necessary to improve the intake installations in accordance with the change in the water level of the river. For instance, due to the closing of tidal inlets, midstream farm land formerly dependent on tidal irrigation has to be adapted to pumping irrigation. There are also cases where the lift of existing pumps need to be changed. And with the birth of a new basin as an irrigation source and as an outlet for drainage—if the improvement works of various irrigation or drainage installations such as sluices and pumps including canal systems are combined—a complete change of water can be achieved.

Where navigation is the most important method of transportation—a characteristic of deltaic areas—careful attention must be given to the locks and similar installations in order to ensure that the navigation channels in and out of the new basin are not cut off and that a new channel is opened.

The change in water quality, from salt water to fresh water, will affect the fisheries of the delta, i.e., marine products will become different. In this case the importance of closed-off fresh water for fish culture should not be overlooked when natural fishery resources are, as at present, gradually decreasing.

One of the new problems of river-water utilization is that, as the water demand for agriculture, industry and other uses increases, water discharge downstream decreases. The result of this situation is a rise in salinity and the water becomes unsuitable for irrigation; even the reduced quantity of fresh water unavoidably flows away to sea. A few of the principal rivers in Japan are equipped with sluices at their estuaries to prevent fresh water from mixing with sea-water at the river's mouth; in this way the total volume of normal discharge can be fully utilized. In deltaic rivers with a gentle slope, the course of back-water flow behind the sluices is so long that the volume of those rivers acting as reservoirs may be a large factor which cannot be overlooked. Of course, if the high-water level of such rivers is maintained for a long time downstream, the problem of irrigation and drainage particularly on both banks of the river, the influence on ground water, and therefore the necessary counter-measures, are interesting from the technical and social points of view.

There are some special problems which require attention, such as maintaining the function of the freshwater basin, the difficulty of draining water into the basin confined by dams, and pollution of fresh water from urban or industrial waste.

DEEPENING OF RIVER BED

One of the characteristics of tidal reaches of deltaic rivers is the phenomenon of coexistent scoring and silting. Due to changes of the river discharge and tidal fluctuation, there is a constant movement of the river bed and of the sand and silt which form the river banks, and for this reason the river changes its course and its depth at many places. This occurrence is particularly true and very active in natural rivers. Accordingly, in rivers where the changes are very marked, channel improvement for purposes such as discharge increase or navigation improvement can never accomplish, by partial dredging, what the natural silting does in volume and in continuity. So the channel improvement in this case should be tackled as a fundamental work handled differently from the problems under discussion here.

The river's estuary, sometimes the middle-reach bed too, should be constantly deepened by dredging in order to maintain the position of the river estuary, to eliminate the injurious effect of back water or to ensure safe navigation. Silting or shifting is no rare occurrence in tidal reaches as a result of contact between fresh and sea-water and of the stagnation of flow brought about by tidal fluctuation. Deepening of the river bed causes a downstream rise of the flood height and also extends the tidal fluctuation farther upstream. Accordingly, the tidal effect will move upstream farther than before and salinity in the tidal part become higher. Moreover, because of the silting moving upstream further deepening becomes necessary. Besides this common phenomenon generally seen all over the world, the effect of deepening the river bed is that storm surges along the river become stronger, thereby raising the river's water level upstream and thus endangering the river's dikes. Such factors should be taken into consideration.

To counteract effects of deepening the river bed, such as the rise in salinity and the moving upstream of the outbreak point of silting, various solutions can be envisaged, i.e., suppressing distributaries by closing them off, separating river from navigation channels, establishing a movable weir and increasing the flushing discharge, etc. However, in the estuary of a large river, each of the above is a difficult engineering task. Therefore, among the feasible measures undertaken first come various methods for increasing the height of river dikes or narrowing the river instead of taking silting prevention measures. Other measures consist of ensuring another water source in place of the salty river water, preventing intrusion of salt water from the river into the land by constructing tidal sluices at the mouth of lateral channels, and establishing freshwater intake installations from the surface water only or by hourly freshwater intakes.

In this way, the maintenance of tidal rivers as a flood control measure and protection against salt-water intrusion have conflicting characteristics which are

the difficult points raised when planning hydraulic works in the delta coastal areas. When all possible methods have failed the inevitable solution might be to transfer the port to another place or to close the estuary.

CONSTRUCTING DAMS IN UPPER CATCHMENTS OF RIVERS

Constructing multi-purpose dams for flood control and water resources development not only affects the upstream valleys but also the downstream deltaic areas, and as the number of dams increases these effects become more salient. One example is the canalizing of rivers which causes an increase of stream velocity and hence of the bed load transported in the middle reach which gradually moves towards the lower reach. But in the tidal reach the levelling of the riverine area continues due to aggradation. In some cases, the lateral water intake, downstream of the apex of the delta, is dammed and sedimentation of sand and silt occurs. Under natural conditions the sequence of dams being built up and broken down changes the deltaic river into a network of anostomozing channels. To prevent this head-works become necessary.

IRRIGATION AND DRAINAGE FACILITIES IN PADDY FIELDS AND UPLAND REGIONS

Utilization and development of land in deltaic areas all over the world, without exception, started with agriculture which has been and is the mainstay of the area. Whether or not agriculture can display a high productivity in deltaic land blessed with favourable natural conditions—fertile soil and flat ground—depends largely on whether or not the utilization and control of water are efficiently carried out. And the desalinization or removal of salt, which is one of the delta problems, can be solved comparatively easily by the adequate control of irrigation and drainage. Furthermore, as deltaic areas are always fortunate in having water in abundance, the efficient utilization of water will favour their further development.

In paddy fields

Rice is the principal crop in most of the world's tropical zone deltas. Accordingly the types and methods of irrigation and drainage used in paddy rice cultivation are governed by the following factors:

1. Choice of crop best suited to natural conditions such as the topography and climate of deltas.
2. Inundation of the plains, either by rainfall or by river flood during the wet season, which is regarded as the natural irrigation, with silt brought to paddy fields by the floods as a good fertilizer.
3. Drainage of paddy fields which is naturally effected by the fall of flood-water level and by evaporation under continuous sunshine during the dry season.

Even in the areas where various major facilities for irrigation and drainage such as embankments, pumps, head-works, sluices and canals are constructed, minor facilities such as ditches and field levees are not yet provided in the paddy fields.

Under such conditions the following effects can be envisaged.

When a sufficient and good irrigation-water supply is ensured, salt and other injurious chemicals from the soil are leached out easily. For instance, a paddy field even newly reclaimed from the sea can be expected to produce a normal yield from the very first year.

When drainage facilities such as sluices, pumps and canals have been newly constructed or improved, not only is the excessive harmful water drained off but the soil in the depressions and creeks can be turned into arable land, contributing to the improvement of sanitary conditions by suppressing brackish water, controlling malaria and ensuring the supply of drinking water.

Through close co-ordination of irrigation and drainage, agricultural improvement is finally attained, and by the combined activities of both, occasionally submerged low-lying land can be reclaimed as good productive land. By utilizing this land and water, higher productive industries and better living conditions can be obtained.

One economic effect of irrigation and drainage improvement is that, taking into account other agricultural improvements, productivity can be increased two or three times. When the increase in productivity and in land acreage resulting from drainage is taken into consideration, the cost of the improvement works can be fully compensated by the production increase. Even if the cost of construction and running the pumps seems too high, the direct and indirect benefits should be taken fully into consideration.

In the course of the development works carried out step by step, however, some of the influences of irrigation and drainage stated below may be encountered and many facts indicate that these influences often create major obstacles.

The increase in water requirements for irrigation along the upper stream naturally causes a decrease in the freshwater discharge of the lower stream, ultimately causing higher salinity in tidal reaches and moving the upper limit of tidal reaches towards the upper stream. In other words this is a case where upper-stream irrigation improvements may cause either a bottle-neck in lower-stream irrigation or salinization damage.

In some cases where river-flood inundation means natural irrigation and when artificial irrigation is utilized, silt-laden water ceases to flow into the paddy fields and might cause a lowering of soil fertility. However, such problems should be examined in each case separately, and the silt-fertilizing effect itself should be scientifically analysed.

Where the constructed irrigation facilities result in

an increased irrigation-water supply, intensive drainage often occurs. Also, it often happens that, as the result of excessive drainage, a shortage in irrigation water jeopardizes the crops. Moreover, the change in the volume of irrigation or drainage water not only influences the water-utilization conditions but also general agricultural conditions such as soil and cultivation.

If the size of a sluice constructed on a natural channel for the purpose of drainage improvement is not large enough, temporary water stagnation may occur since the maximum discharge cannot be drained and remains the same as under the former conditions.

Conditions in creeks and channels are changed by the various installations such as sluices, canals, pumps and dikes, etc., constructed for irrigation and drainage improvement purposes, particularly in deltas where industry and livelihood largely depend on the network of canals more than on the network of roads. Sometimes transportation is hampered temporarily.

In upland regions

There is no significant difference between paddy field and upland irrigation and drainage, but there is a problem concerning the choice of crops. Attention should be given to the selection of crops suitable to the land and water conditions of the district and breeding improvements be made to suit field conditions—for instance, if waterlogging becomes a problem in upland fields, they should be converted into paddy fields. On the other hand, when there is a shortage in the irrigation-water supply, paddy fields should be adapted to the cultivation of rice varieties requiring less water.

RECLAMATION

Deltaic land is a present of Nature, but man can help Nature by two processes of reclamation: impoldering and artificial filling-in. These two methods have nowadays gained an important place in the development projects of deltaic areas.

Impoldering work

The very origin of impoldering work was to protect low-lying land against submersion under river or sea at high water; the protection work developed into reclaiming sea-bottom or river-bed ground, sometimes several metres under normal water level in the Netherlands and Japan. In some tropical-zone deltas, reclamation of tidal land is carried out where the land elevation does not reach the high-water level of sea or river.

Characteristics which were previously described for deltas apply to polders as well. In the course of poldering various phenomena occur:

1. Where tidal sluices are installed for gravity drainage and where the foreland rises due to tidal sedimentation, the tidal channel is eventually filled up and sluices cease to function. If a new polder on the elevated foreland is secured by dikes and sluices drainage of the old polder is improved. Successive reclamations carried out in this way constitute the history of impoldering.
2. In low-lying polder lands, brackish water and its removal are a constant problem. Brackish water invades polders by seeping through the dike and permeable soil layers. Salt water flowing over or breaking through the polder dike, and brackish water stagnating in creeks, depressions or paddy fields may cause damage to crops. Salt damage can be avoided practically without difficulty in the case of paddy fields, if there are good irrigation and drainage installations. That is, salt in paddy fields can easily be leached out by irrigation and drainage, and saline water in canals (creeks) or retarding ponds (depressions) is drained out by pumps or sluices before it causes damage to crops. Seepage can be reduced by means of protective works on the outer slope of the dike, or in the foreland; the water still seeping from the foreland is collected in a canal running along the inner slope of the dike.
3. Clearly, various kinds of hydraulic changes occur on the water surface near the new polders when a portion of the sea or lake surface is occupied by polders. For instance, if a bay is closed by a dike at the mouth or if a large portion of the bay is reclaimed the tidal conditions along that part of the sea coast may change considerably.
4. Impoldering is only carried out if there is a strong need for it. During their subsequent development polders may become urbanized or even industrialized. Then new problems crop up such as the control and utilization of water, land and water traffic, settlement and sustaining strength of reclaimed ground.

Sand-filling works

The favourable composition of the soils in the area under discussion makes hydraulic works easy. This may contribute to the rise of industries in these coastal districts.

Deltas are not blessed with mineral resources but owing to three important factors—sand, water and population—they have great possibilities in future industrial development. For the development of new industrial districts problems such as deepening anchorages and channels for the use of large freighters might become important.

CONCLUSION

Since human interference with Nature can bring about changes that are so important, the possible influence

and consequences of development projects must be studied carefully. In order to evaluate their effect the knowledge of Nature itself is indispensable and can only be obtained by thorough basic investigations of the manifold powers co-operating in the formation of regional structures. Further progress in science and techniques is urgently needed to contribute to the betterment and welfare of the human race.

Résumé

Influence des ouvrages hydrauliques sur le milieu naturel (K. Deguchi)

Depuis des siècles, dans la plupart des deltas du monde, l'homme construit ou étudie des ouvrages hydrauliques de toutes sortes afin de mettre en valeur la région avoisinante, et ce sont ces travaux d'aménagement du sol ou des cours d'eau qui permettent l'utilisation maximale des deltas. Mais la construction de grands ouvrages hydrauliques entraîne une certaine réorganisation du milieu naturel qui exerce une influence importante aussi bien sur le plan physique que sur le plan humain.

Dans l'étude de l'influence des ouvrages hydrauliques, il faut tenir compte du fait que les deltas se sont développés progressivement par un processus naturel, qui a parfois donné des résultats inattendus. L'auteur signale certains exemples particulièrement intéressants et en donne l'explication. Parmi les travaux qu'il étudie, on relève la transformation d'eaux saumâtres en un bassin d'eau douce; le creusement du lit d'un fleuve pour en accroître le débit ou pour améliorer la navigation; la construction d'un barrage dans le cours supérieur; l'amélioration de l'irrigation et du drainage; la récupération de terres par assèchement de polders ou par comblement avec du sable.

Les problèmes des eaux salées peuvent être étudiés en même temps que ceux de l'irrigation et du drainage. Mais la régularisation du régime des eaux dans les deltas est très difficile, parce que le niveau de l'eau est généralement peu élevé, sauf dans certaines périodes de crue ou de tempête, ce qui rend la solution du problème très complexe et trop coûteuse.

Il faudrait donc faire preuve d'une grande prudence en modifiant l'équilibre hydraulique précaire qui s'est établi dans les deltas et suivre pour cela un plan d'ensemble fondé sur des renseignements exacts provenant d'une étude très sérieuse, sans jamais perdre de vue les causes et les effets de toute modification des conditions naturelles.

Discussion

V. N. Nagaraja. Dr. Deguchi has vast experience of deltaic problems and problems of reclamation. He has also first-hand knowledge of a number of deltaic areas in various stages of development.

He has very rightly emphasized that any reclamation work is likely to affect the delicate hydromorphological balance. I shall, however, emphasize one known feature of the deltas of the Sunderbans type. The Kojima Bay and Zuider Zee are not strictly comparable to the Ganges delta, for instance. The Ganges delta is in a delicate balance, contributed by upland discharge, silt load and tidal action. Human interference by premature reclamation and encroachment into riverine channels has already manifestly upset that balance. Instead of building up new land, the river silt is silting up river beds. This at once leads me to the point I am driving at.

During the ECAFE symposium in July last year, it was recognized that water management was a very important factor in deltaic development. This has been listed as an important topic for another symposium. I feel that it shoud includle silt management also because, as I have said earlier, silt plays a very important role in deltaic activity.

Closures like the Kojima Bay in Japan and Zuider Zee in Holland have certainly provided habitation and prosperity for large sections of the people. Similar works in the Gangetic delta, for instance, can have far-reaching repercussions not seen in these areas. The Ganges-Brahmaputra system is known to bring a vast amount of silt every year, over 1,300 million tons a year. Unless this is disposed of in a scientific manner, it is bound to generate very complex problems. How do the barriers of the Kojima type affect the situation? An answer to this question will condition the approach to the problem of the Ganges delta. The life of the sweet-water reservoirs artificially created will gradually shrink in size and the water-silt-salt balance will undergo great changes. This aspect should be studied in detail in all new closure works.

The progress of the river deltas in Java

F. Hollerwöger[1]

INTRODUCTION

(by Professor Iso Reksohadiprodjo)

Before the Second World War, first in my capacity of Inspector of the Agricultural Extension Service of the Central Java Province, then as Head of the Section of Economics of Bogor Residency, I brought the erosion problem several times to the attention of authorities. In order to stress the warnings of Nature, I pointed out (a) the frequently occurring starvation-oedema; (b) the devastation of forests resulting in heavy floods in the rainy monsoon season and the scarcity of water in the dry season; (c) the acceleration of the growth of river deltas along Java's northern coast (markedly enhanced during and after the war).

After the establishment in December 1949 of Gadjah Mada University in Jogjakarta and the Faculty of Agriculture and Forestry, we were fortunate to obtain the help of a highly experienced technician, Diplom. Ingenieur Franz Hollerwöger, as lecturer in geodesy and aerial photography.

Regarding (c) above, Mr. Hollerwöger readily promised to produce a paper on that subject, because maps and aerial photographs were at his disposal in the Forestry Research Institute in Bogor, indicating clearly the growth of river deltas in Java.

The paper presented here is a summarized report of the results obtained by Mr. Hollerwöger and his assistants in Bogor; planimeter calculations were done by Ir. Ali Djojoadinoto, lecturer in the analysis of variance and geodesy, and his staff in Bandung, assisted by Mr. Soeharto of the Technical Faculty of Gadjah Mada University (see Table 1). To all these contributors we extend our warmest feelings of gratitude.

With a view to our president's slogan to keep in mind the "suffering of our people", we may illustrate Mr. Hollerwöger's general conclusion with another slogan, "the suffering of our soils", of which the Minister of Agriculture, Brigadier-General Azis Saleh, said that we would perish within a short time if, owing to our negligence, the top soil of our country were washed away into the ocean or destroyed by erosion.

Data are in evidence in the following report. Data, which do not lie. Data, indicating how, in the last decades, the devastation of forests and estates under perennial crops has resulted in an accelerated growth of river deltas three, even four times as fast as before.

TABLE 1. Increase of river deltas along the north coast of Java[1]

River	Period	Planimetered increase (in square kilometres)	
		During period	Average during one year in period
Fjipunegara	1869-1934	18.4	0.28308
	1934-1946	10.7	0.89167
Tjimanuk	1857-1917	26.0	0.43333
	1917-1935	20.1	1.11667
Bangkaderes	1853-1922	8.8	0.12754
	1922-1946	3.0	0.12500
Sanggarang	1866-1922	18.0	0.32143
and Bosok	1922-1946	18.1	0.75417
Pemali	1865-1920	7.1	0.12909
	1920-1946	10.8	0.41538
Tjamal	1870-1920	2.2	0.04400
	1920-1946	6.2	0.23846
Bodri	1864-1910	5.9	0.12826
	1910-1946	15.2	0.42222

1. Computed by the Office of Hydrology of the Department of Public Works and Energy, Bandung. Based on maps produced by Diplom. Ingenieur Franz Hollerwöger. (By courtesy of Professor Ali Djojoadinoto, Bandung.)

1. Diplom. Ingenieur Franz Hollerwöger was, before the war, in the Surveying Service of the Netherlands Indies Forestry Department; after the war he served in the Forestry Research Institute in Bogor and was also assigned as lecturer at the Faculty of Agriculture and Forestry of Gadjah Mada University until 1958. Since then he has retired and returned to Austria, his home country.

GENERAL

When flying above the north coast of Java several deltas may be seen but above the south coast no deltas are observed. Is there no deterioration of the soil, no erosion on the south coast? On the northern and southern part of the island, of course, the same deterioration and erosion are to be found, but on the south coast the heavy breakers of the Indian Ocean, the tide and the currents remove all the mud, sands and other sediments brought to the sea by the rivers.

On the north coast there is no surf, only small currents and the difference between low and high tide is very small, about 0.5 metre, so deltas may be formed. These deltas are formed by mud, sand and other sediments resulting from the soil's deterioration.

The slower the rivers flow, the more the sediments sink to the bottom forming soft muddy banks and flats and finally deltas.

The deterioration of the soil depends on the climate, topography, geology, soil and the vegetation on the soil. All these factors will be discussed in the description of the different rivers.

The deterioration of the soil can be calculated by measuring the quantities of sediments. The yearly erosion figures for the different rivers and materials are also known, for instance:

For the Tjiliwung, near Bogor, 0.1 mm./year (volcanic soil).

For the Tjimanuk, 0.42 mm./year (volcanic products, marl, lateritic soil).

For the Pengaron, near Semarang, 4.3 mm./year (marl, limestone, lateritic soil).

For the Seraju, near Tjilatjap, 1.6 mm./year (volcanic products, marl, lateritic soil).

In this research, however, we are studying the delta formation with the aid of topographic maps and vertical aerial photographs covering a period of nearly 100 years (for some deltas 92 years).

The quantity of the sediments cannot be calculated because we do not know how many sediments are deposited in the sea.[1]

THE BASIS OF THIS RESEARCH

The Colonial Government ordered, by Decree No. 8, the survey of the counties (*residenties*) in Java. The survey of Cheribon county was ordered by Decree No. 10 of 25 December 1853 and was completed in 1857. This surveying began in 1863 in the important counties on the north coast, on a scale of 1 : 100,000. It was done with compass traverses and tapes. The compass instrument used was the "Schmalkalder Bussole."

Because in Indonesia the differences between the magnetic and the astronomic azimuths are very small and constant, this method of surveying is very good. The Agone (the line where magnetic and astronomic azimuth are the same) has only changed between 1600 and 1950 from central Borneo to central Sumatra. The variation at Bogor during 25 years is only one-third of a degree.

A number of European military officers carried out this survey in an excellent way. The cartographic representation was based on hatches and colours. Erwin Raisz, lecturer at Harvard University, mentioned the very good quality of these maps in his book *General Cartography*.

The maps give a clear picture of the different river deltas and other details. They have been copied and form the first basis of our research.

The river deltas are also shown on the topographical maps of Java (scale 1 : 50,000). These maps are based on a triangulation system and are of excellent scientific quality. They are printed in seven colours. The relief is shown by contour lines at intervals of 25 metres.

The deltas concerned were mapped during the years 1910 to 1941. These maps have been reduced to the scale of 1 : 100,000 and form the second basis of our research.

Compiling data for river deltas from the county maps and from the topographical maps was easy, but for some of them the compilation had to be done by taking the maps one by one.

On the vertical aerial photographs (scale about 1 : 50,000) made in 1946, the rivers are also clearly shown. These vertical photos have been rectified and compiled with the topographical maps (1 : 50,000).

The aerial photographs show clearly that the sea near the coast is sometimes very shallow with varying mud banks, but here we will mention only the small islands and muddy banks that rise out of the sea.

During a trip by motorboat along the *Rhizophora* forests on the north coast, our boat had to stop about a kilometre from the coast. We left the boat and, wading in the sea, dragged it to the shore. The water was only 0.5 metre deep.

DESCRIPTION OF THE RIVER DELTAS

River Tjipunegara

The watershed area of this river is 1,450 sq. km. The average rainfall in the mountains is 4,947 mm./year, with a daily maximum of 335 mm. (Station Pajung, 1,100 metres); in the hilly region 2,943 mm./year, with a daily maximum of 265 mm. (Station Bantarwaru, 50 metres); in the plain 1,699 mm./year, with a daily maximum of 205 mm. (Station Losari, 4 metres).

The river and its tributary have their sources in the high mountain ridges of the Preanger boundaries, nearly 2,200 metres above sea level.

In the plain the river is meandering.

Nearly one-third of the area is in the mountains and

1. Although this is quite true in an absolute sense, and although this quantity of sediments cannot be computed by planimeter-contouring, a relative comparison may be presented. This is demonstrated by the computation carried out by Professor Ir. Ali Djojoadinoto, shown in Table 1.

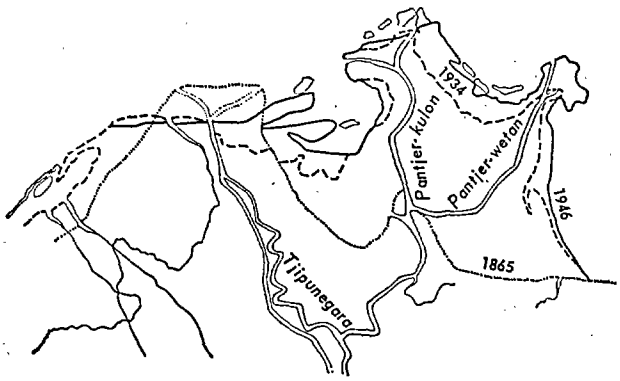

FIG. 1. Growth of the delta of the Tjipunegara (Purwakarta, West Java, Indonesia). Coastlines of 1865, 1934 and 1946. Scale 1 : 50,000.

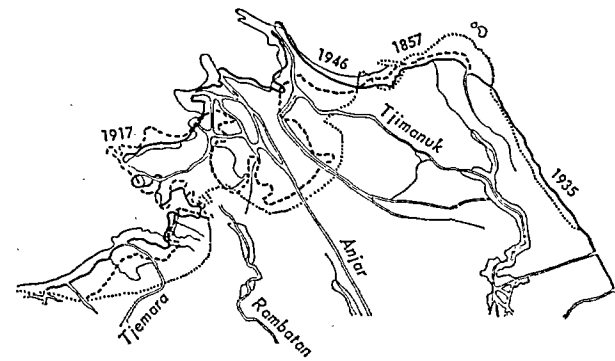

FIG. 2. Growth of the delta of the Tjimanuk (Cheribon, West Java, Indonesia). Coastlines of 1857, 1917, 1935 and 1946. Scale 1 : 50,000.

is covered with primary deciduous rain forest, tea plantations and dry-land farming. Another third is hilly land, covered with teak forest, rubber plantations and dry-land farming.

The remaining third is flat, irrigated rice-fields, sisal plantations and, on the coast, *Rhizophora* forests.

On the maps of 1866, the rice-fields on both sides of the river almost reach the sea coast. A road leads from the Chinese camp Pamanukan to the sea-shore. In former times there must have been rhinoceres in this area, because we find the word *badak* (rhinoceros) in the names of different places. The main road shows milestones (1.5 km. apart) and every 5 miles along is a control station (Post Gempol, Post Bugel, etc.).

The river splits in two near the village Tegallurung and forms the Tjipunegara and Bobos rivers. These rivers divide again into two tributaries near the coast (see Fig. 1).

The topographical maps from the year 1939/1940 show that the new delta of the Bobos (now called Pantjer) stretches out 3.5 to 4 km. into the Java Sea, while that of the Tjipunegara has decreased by about 1 or 1.5 km. Aerial photographs from the year 1946 give the latest situation.

It must be mentioned that in the year 1936 the *Rhizophora* forests on the north coast of Java were mapped from the vertical aerial photographs on a scale of 1 : 20,000. With these new maps a forest inventory has been made. The coastline is nearly the same as on the maps of 1940. The increase from the years 1865-1869 to 1940 is about 4 km. on the Pantjer-kulon and about 5 km. on the Pantjer-wetan. The decrease at the river mouth of the Tjipunegara is about 600 metres for the same period. The increase between the years 1940 and 1946 is about 600 metres at the river mouth of the Pantjer and on the sea coast.

River Tjimanuk

The Tjimanuk is one of the big rivers on the north coast of Java. The watershed area of this river and its tributary is 3,650 sq. km. Its sources are situated on the Preanger volcanoes and on the volcano Tjireme, 2,000 metres and 3,075 metres above sea level, respectively.

The average rainfall in the mountain is about 4,128 mm./year, with a daily maximum of 187 mm. (Station Lemahputih, 1,095 metres); in the hilly region 3,951 mm./year. with a daily maximum of 258 mm. (Station Madja, 600 metres); in the plain 1,621 mm./year, with a daily maximum of 317 mm. (Station Indramaju, 10 metres).

Nearly one-third of this area is situated in that steep, volcanic region, mainly covered with tropical rain forests. There are also many tea plantations and dry fields.

Nearly another third is formed by hilly, sometimes very eroded land. In this part the very steep Kromong hills are unproductive, eroded, barren country and the "dying country" (*stervend land*) shows devastated steep ridges, absolutely denuded. But in many spots there are also teak forests.

The plains form the remaining third of this river area in which there are terraced, very fertile, irrigated rice-fields. Many sugar factories are found in this area, a large part of which consists of huge teak forests of very poor quality. The coastal region is covered with tidal forests.

The main river splits into two big affluents near Ploembon forming the Tjimanuk and the Rambatan rivers. The Tjimanuk again splits into two affluents near Pabeanhilir (see Fig. 2).

The 1917 topographic map shows a newly-dug irrigation canal from Losarang to Tjemara. In the vicinity of the latter a new delta was formed which extends from 1.5 to 2.5 km. into the sea. The Rambatan has also built up a new huge delta 3.5 km. to the north-east and 3 km. to the north. The oval-shaped form of the 1857 delta shows an increase of 400 metres only during this 60-year period. The river bed of the Tjimanuk was lengthened by 2.5 km. in a west-north-west direction into the Java Sea. On the other hand, part of the coast, nearly 700 metres wide, has disappeared.

The tidal forests near the river mouth have been mapped (scale 1 : 20,000) from the vertical aerial photographs of 1935.

The new coastline demonstrates a considerable augmentation, up to 1 km. to the north-north-west in the vicinity of Tjemara. The increase of the delta in the direction of the newly-dug irrigation canal Kali Anjar was about 6 km. The river bed of the Tjimanuk was lengthened by 2.5 km. in a west-north-west direction. All these changes occurred within a period of only 17 years.

The biggest increase of about 350 metres per year is to be seen on the irrigation canal.

Vertical aerial photographs of the year 1946 show an increase of 1.2 km. for the irrigation canal, of 1.8 km. for the Tjimanuk and of 0.5 km. for the Tjemara. The decrease of the Rambatan is approximately 300 metres.

River Bangkaderes

This is a small river with a watershed area of 250 sq. km., but it has formed a large delta north of the main road from Tjirebon to Losari (see Fig. 3). The river's area including its affluents is situated east of the main road from Tjilimus to Kuningan and north of the road from Djalaksana to Tjiawigebang. Half of the area is hilly country, with unproductive and strongly eroded soils. There are also poor teak forests. Kuningan is situated about 480 metres above sea level. The average rainfall in the hills is about 2,723 mm./year with a daily maximum of 184 mm. (Station Kuningan, 480 metres).

The other half of the area consists of plains covered with terraced rice-fields. There are also sugar-cane factories. The newly-formed delta areas are covered with tidal forests. The average rainfall in the plains is about 2,198 mm./year, with a daily maximum of about 202 mm. (Station Lemahabang, 11 metres).

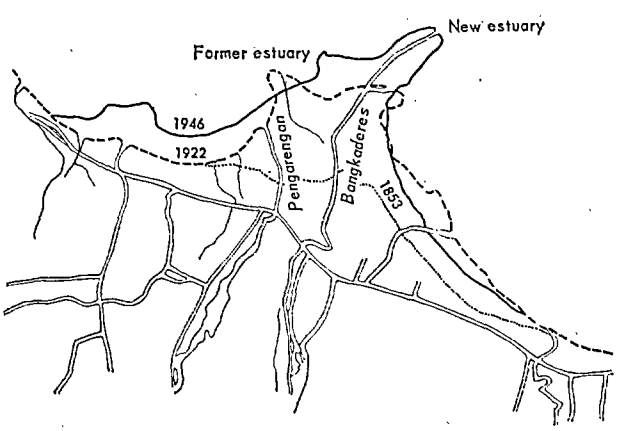

FIG. 3. Growth of the delta of the Bangkaderes. (Cheribon, West Java, Indonesia). Coastlines of 1853, 1922 and 1946. Scale 1 : 50,000.

An 1857 map shows a rich rice-producing country with many roads. There is also a sugar-cane plant. On the sea-shore, north of the main road, are tidal forests. The river has a big estuary.

The topographic map of the western part was drawn in 1941, that of the eastern part in 1922. Both the main railroads from Tjirebon to Jogba and from Tjirebon to Semarang cross this country. Sidanglaut, the sugar-cane processing plant shown on the 1857 map and situated near Lemahabang still exists. The map shows different tramway lines which were constructed for conveying the cane to the processing plant.

Between the years 1857 and 1922, that is within a period of 65 years, there was a striking increase of 1.5 km., 2.7 km. and 2.2 km. of the Bangkaderes West river, and the East. The very small Kantji river now has dams on both sides for about 3 km., an indication that the flood situation is dangerous.

Aerial photographs of 1946 show the latest situation. The tributary Bangkaderes West disappeared in the period 1922-1946. There is a considerable increase—of about 1.8 km.—near the mouth of the Bangkaderes East and of about 1 km. to the north. The mouth of the Bangkaderes West decreased for about 600 metres and the coastline north of Bandungan has also decreased.

The sea-shore north of the mouth of the small Kantji river shows a new delta about 1 km. wide.

It is a striking fact that during the second period —which lasted 24 years from 1922 to 1946—delta formation was as large as during the first period—from 1857 to 1922—which was nearly three times longer. Only a detailed examination of the river area concerning the variation of the vegetation and the ground cover can give an explanation of this increase of the deltas.

Rivers Sanggarung and Bosok

The river watershed area is 940 sq. km. The river and its tributary have their sources on the boundaries of Priangan, Banjumas and Pekalongan counties as well as on the volcano Tjireme, 3,075 metres above sea level.

Half of the area consists of very steep mountainous country covered in the higher regions with rain forests. There are no plantations, which may indicate that the soil is not very good. The boundary mountains are about 1,400 metres above sea level. The average rainfall on the top of Tjireme is 2,818 mm./year, the daily maximum is unknown. (Station Kuningan at 480 metres has a rainfall of 2,723 mm./year with a daily maximum of about 184 mm.).

One-quarter of the area is hilly country covered with poor rain forests and poor teak forests. It is also used for dry-land farming by the population. The average rainfall is about 2,647 mm./year, with a daily maximum of 240 mm. (Station Tjiawigebang, 225 metres).

Another quarter of the area consists of irrigated,

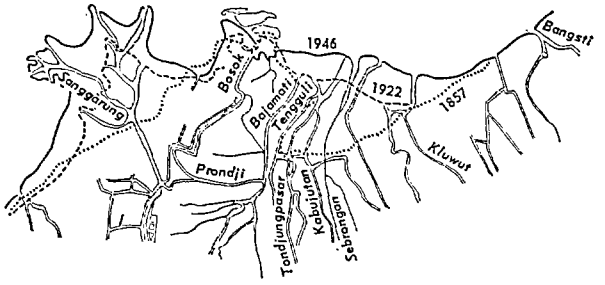

FIG. 4. Growth of the deltas of the Sanggarung and Bosok. (Cheribon, West Java, Indonesia). Coastlines of 1857, 1922 and 1946. Scale 1 : 50,000.

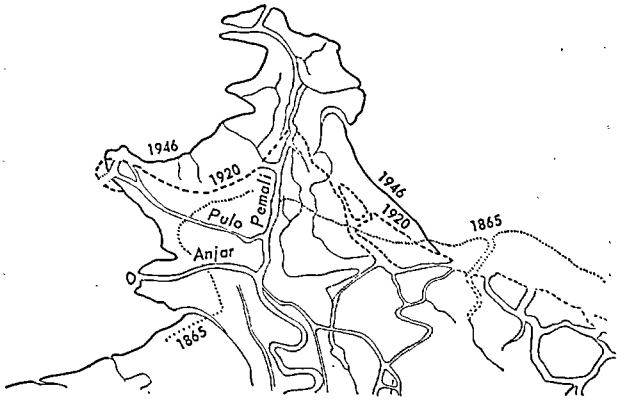

FIG. 5. Growth of the delta of the Pemali. (Pekalongan, Central Java, Indonesia). Coastlines of 1865, 1920 and 1946. Scale 1 : 50,000.

terraced rice-fields. There are also sugar-cane plantations. The coast is covered by tidal forests. From Tjibeureum the Sanggarung is meandering for about 35 km. North of Losari around 1920 a new river bed was dug. Very large dams were built on both sides of the new river to avoid floods in the rice-fields. Outside the dams the river has built up a new large delta. The rivers splits into four affluents, the main affluent again forming three affluents. The old Sanggarung river is now called Bosok and has built up three small islands situated east of the mouth. This river also joins up with the small rivers Bajamati, Tengguli and Kabujutan (see Fig. 4). Along all these rivers and along the Bakakan and Kluwut there are huge dams to prevent flood damage to the rice-fields. The average rainfall in the plain is about 1,699 mm./year, with a daily maximum of about 205 mm. (Station Losari, 4 metres).

The 1857 map shows that the western part of the river area is situated in the earlier Cheribon county, the boundary of which is formed by the river. The eastern part is in Tegal county and was mapped in the years 1863-1866. The old map shows rich, terraced rice-fields on both sides of the main road leading to Losari, Tandjung and Kamuragang. Large villages are situated on both sides of the Sanggarung river. This river joins up with the small rivers Tandjung, Gago and Kluwut.

The 1941 topographical map for the west and that of 1921 for the centre and the east show a rich, irrigated, rice-producing country. All the rivers are flowing now between large dams to avoid flooding in the rice-fields. There are sugar-cane plantations. Tidal forests are found along the shore. The Sanggarung splits into different channels which bring the flood-waters to the sea. These are always a very muddy brown, as can be seen when travelling by air. The Bosok splits near Pangabean into the river Prondji which is linked with the rivers Bajamati and Tengguli. All these rivers together with the Kabujutan and Kluwut, now form a big delta.

Aerial photographs from the year 1946 give the latest situation. The delta has been widened near Tjiberu by about 0.5 km. The delta of the most western affluents is 0.4 km. wider. Another affluent has formed a new large delta, 2.8 km. wide, with different tributaries and this delta widened by 2.5 and 2 km. The delta of the Bosok decreased by 1.4 km.

The Bajamati, Tengguli, Kabujutan, Sebrongan and Kluwut have formed one single huge delta. They are connected with each other and the delta has widened.

River Pemali

The watershed area of the river is about 1,200 sq. km. The western boundary is formed by a line from Kelompok to Sitanggal, Larangan and Sindangdjojo, up to the top of the mountain *Gunung* Kumbang (1,218 metres); then the boundary follows the steep ridge of this mountain to *Gunung* Kadako (1,078 metres).

The sources of this river are situated on the high steep mountain ridges forming the boundary with Banjumas county. On this boundary are situated *Gunung* Podjoktiga (1,347 metres), *Gunung* Pajung (748 metres) and *Gunung* Merajung (748 metres).

This boundary then crosses the main railroad near Kranggan. Hereafter the boundary follows the steep mountain ridges up to the volcano *Gunung* Slamet (3,420 metres).

The eastern boundary is formed by a line from the top of the volcano *Gunung* Slamet to Djedjeg, Balapulang, Djatibarang, then north to the sea.

One-quarter of this area of the Pemali consists of very steep mountainous regions which are covered, only in the higher part, with rain forests. There are no plantations in this area, an indication that the soil is not of good quality. The part of this area that is situated east of the railroad is formed by the volcano *Gunung* Slamet and its steep ridges. All these areas are covered with primary deciduous rain forests. The average rainfall is about 3,266 mm./year, with a

daily maximum of 240 mm. (Station Dawuhan (Igir Klantjeng), 1,531 metres).

Another quarter of the area is hilly country covered with huge teak forests and used by the population for dry-land farming. The average rainfall is about 2,880 mm./year, with a daily maximum of 286 mm. (Station Bumiaju, 152 metres).

The remaining half of this watershed area consists of plains with rich, irrigated rice-fields. There are sugar-cane factories. The region along the shore is covered with tidal forests. Very large villages are situated on the shores of the river. The average rainfall is 1,871 mm./year, with a daily maximum of about 210 mm. (Station Brebes, 3 metres).

The map of the years 1863-1866 shows a rich, rice-producing area and the township of Brebes, the residence of a high local official (*Bupati*). The main road crosses this country from Pakidjan to Brebes and Kaligangsa. The main road shows milestones (1.5 km. apart) and different control stations. The coast is covered with tidal forests and swamps from 2 to 4 km. wide.

The 1920 topographical map shows a newly-formed delta in the direction of the west and the north. Compared with the 1863-1866 map this delta progressed by 1.8 km. on the tributary Anjar, by about 2.5 km. on the tributary Pulo and by about 1.8 km. on the tributary Pemali (see Fig. 5).

The coastline north and west of Muara Bujiran decreased by about 0.7 to 1 km.

The 1946 aerial photographs show the latest situation. The mouth of the Anjar has not changed; the length of the Pulo has increased to the north-west by about 0.5 km; but the delta of the Pemali shows a large increase, of about 2.7 km., in a northerly direction.

It is surprising that the increase of the delta for the first period, which lasted 56 years, was only 1.8 km. and that for the second period, lasting only 26 years, it was 2.7 km. In the second period, half as long as the first, the increase of this delta was 50 per cent higher.

Only a detailed examination of this watershed area can explain this difference in the delta's increase. As a result of this examination methods to prevent deterioration of the land could perhaps be found.

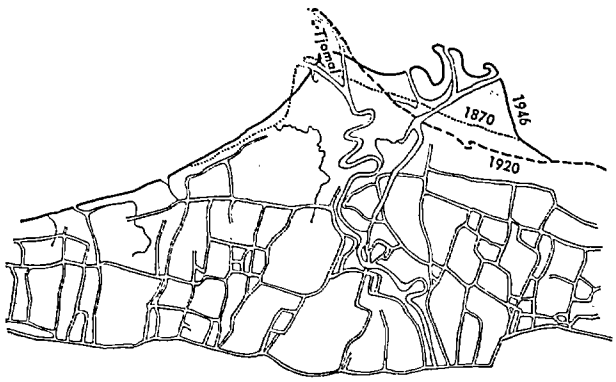

FIG. 6. Growth of the delta of the Tjomal (Pekalongan, Central Java, Indonesia). Coastlines of 1870, 1920 and 1946. Scale 1 : 50,000.

River Tjomal

The watershed area of this river is about 710 sq. km. Its western boundary is given by a line from the river mouth to Patarukan, Bantarboland, Randudongkal, then to the top of *Gunung* Botak following the mountain ridge to the mountain Plakaran and the steep ridge up to the volcano *Gunung* Slamet (3,428 metres). The sources of this river are situated in the steep, mountainous ridges of *Gunung* Slamet and on the boundary of the Banjumas and Pekalongan counties where we find the summits *Gunung* Pulusari (1,134 metres), *Gunung* Djaho (1,303 metres), *Gunung* Banowati and *Gunung* Langit (1,623 metres).

The eastern boundary is formed by the mountain ridges of *Gunung* Langit to Sembodja, then by a line to Sitatan, Kandangserang, Kesesi, Muntjang, Uludjami and to the river mouth (see Fig. 6).

One-third of the watershed area is very high, steep and mountainous, only partly covered with rain forests. It is very denuded and unproductive, therefore transmigration of the population was sometimes necessary, i.e., in the Paninggaran district in 1953-1954. Around 1850 part of this country was used by the government for coffee plantations. From Sukawati the river meanders along 24 km. approximately. The average rainfall is 5,110 mm./year, with a daily maximum of about 358 mm. (Station Belik, 755 metres).

Another third of the area is hilly country partly covered with teak and rain forests and a rubber plantation owned by the government. Part of it is used by the population for dry-land farming. The average rainfall is about 4,564 mm./year, with a daily maximum of 240 mm. (Station Gembungan, Buaran rubber plantation).

The remaining third is situated in the plain and covered with rich irrigated rice-fields. The coast is covered with tidal forests.

The 1866 map shows a densely populated rice-producing country, traversed by the main road from Pemalang to Kebandaran. The main road has many control stations (e.g., Pemalang, Post Petarukan, Post Djatigarang). At Tjomal there was a sugar-cane factory which still exists today. There are numerous villages on the shores of the river.

The delta is not large and it is remarkable that no tributaries are shown on the map. We can probably conclude that in 1866 the tree-covering of the "hinterland" was much more effective than it is today, therefore there must have been less deterioration and erosion.

The 1921 topographic map shows that the course of the river Tjomal has changed. Some bends have disappeared, i.e., Pandjuan and near Penambangan. The river has built up a delta about 2.5 km. to the

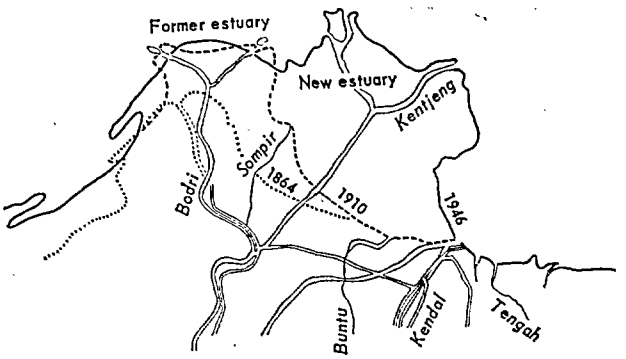

FIG. 7. Growth of the delta of the Bodri (Semarang, Central Java, Indonesia). Coastlines of 1864, 1910 and 1946. Scale 1 : 50,000.

north. The old "Hoek van Pemalang" has disappeared along approximately 0.6 km. and north of Sigedong part of the coast has disappeared also along roughly 0.5 km.

Aerial photographs made in 1946 show that near Kandang the river has formed a new bed and has completely changed its course. Part of the old river has disappeared, also part of the river mouth (about 1.8 km.). The new river has built up a large delta formed by three tributaries with an increase of 2.7 to 3.2 km. The delta-building rate of this river was much higher in the last period of 26 years than in the earlier period of 55 years.

River Bodri

The watershed area of this river is 640 sq. km. The western and southern boundaries are formed by a line going from the river mouth to Tjipiring, Sedjomerto, Sukoredjo, to the top of the volcano *Gunung* Prahu (2,566 metres) and by the boundary between the Kedu and Semarang counties from the Perahu to the volcano Sindoro (3,136 metres); thereon by a line going to Muntung, to the top of *Gunung* Beser (1,030 metres), to Karangseneng, to the top of *Gunung* Tengkek, to Lamuk, Kenteng, and finally to the volcano *Gunung* Ungaran (2,030 metres).

The eastern boundary is formed by a line from the volcano Ungaran to Blewah, Ngareanak, Tjatjaban, Duren, Patebon and to the river mouth (see Fig. 7).

The sources of the river are partly found on the volcano Prahu (2,566 metres), on the southern boundary, and on the volcano Sindoro, *Gunung* Beser, *Gunung* Tengkek and the volcano *Gunung* Ungaran. After about 30 km. in the plain, near Djuwero, the Tjomal begins to meander.

Half of this area is very steep, volcanic country partly covered with primary deciduous rain forests. Many plantations are located there, mostly planted with coffee. The population is using part of this area for dry-land farming and for rice-fields on the shores of the tributary. The average rainfall is about 5,291 mm./year, with a daily maximum of 346 mm. (Station Genting Gunung, 1,123 metres).

One-quarter of the area is hilly country, covered in part with huge teak forests and used for plantations. Part of it is used by the population for dry-land farming. The average rainfall is about 3,454 mm./year, with a daily maximum of about 261 mm. (Station Bodja, 294 metres).

Another quarter of this area, situated in the plains, is covered with rich, irrigated rice-fields. Some sugar-cane factories are found there. The average rainfall is about 1,957 mm./year, with a daily maximum of about 270 mm. (Station Kendal, 2 metres).

The 1861-1864 map shows a very rich, densely populated, rice-producing country. The rice-fields extend to the sea shores. There are no tidal forests and only very small swamps. The main road from Truko to Kendal and Karangtengah crosses this country. Numerous villages are seen along the roads and rivers. The delta is not large and has only one tributary; it is covered with rice-fields extending to the coastline. The situation shown on the 1861-1863 map gives a clear picture of this period where there was no significant increase of delta formation. As regards erosion and denudation, the general situation in this watershed area must have been very stable.

The 1910 topographical map shows few changes in the situation: only the main railroad crosses the country, but different tramlines are to be seen which were used to convey teak wood and sugar-cane to the processing plants. The delta has increased by about 1.7 km. and 1.8 km. Some tidal forests are in the eastern part of the delta. The shore, north of Kalingaglik, also increased by about 0.7 km and the coastline from Sumurbinangun to the affluent Sompir by about 1.4 km.

During the period from 1910 to 1946 a new affluent, the river Kentjeng, was formed, probably dug out; it splits into two tributaries and has built up a very large new delta, with an increase of about 4.2 km. near Tandjung Kentjeng and of about 4.1 km. near Tandjung Karawetang. Aerial photographs show also that this new delta is covered with tidal forests. The old delta of the Bodri has increased and decreased by about 0.2 km and about 0.4 km. respectively. This river also shows, for the second period of 36 years, an increase twice as high as that of the first period which lasted 10 years longer, i.e., 46 years. Only a detailed examination can explain this very high increase of the delta.

CONCLUSIONS

1. Examination of the maps shows that delta formation has greatly progressed during the last decades. The deltas of the rivers Bangkaderes, Sanggarung-Bosok, Pemali and Bodri were extraordinarily enlarged.

Perhaps the population increase in the hills and mountains of these regions can be attributed to deforestation on a big scale and to their use for dry-land farming.[1]

It is often said that delta formation is land augmentation, but our maps clearly show that, on the contrary, many already-formed deltas are reduced by the action of the sea.[2]

In any case, the humus layers which come from mountains, hills and dry-land farming fields descend at an increasing rate. The land shows the effects of denudation and deterioration on a large scale. The unproductive Kromong hills and the "dying country" (*stervend land*) illustrate the final results of this situation.

2. On the other hand, river sedimentation raises the river beds. Already small floods inundate the rice-fields along the shores and damage the crops. Therefore, large dams have been constructed along nearly all the rivers mentioned. Nevertheless, every year, in the months of January and February, the main railways near those rivers are inundated, e.g., near the Tjomal and Bodri.
3. In different parts of those watershed areas large reservoirs are now being constructed. However, there is the danger of these reservoirs being filled up by river sediments within a very short time.
4. All these facts show that it is of primary importance that land deterioration on such a large scale be stopped or at least considerably reduced.

1. Another possibility is the devastation of estates during the Second World War, when the Japanese, having no interest at all in export products, left several estates to the mercy of the Indonesian farmers, who planted annual crops after having cut down the heavy tree-cover.
2. Moreover the delta's growth is only made possible by loss of the fertile top soil in the hills.

First, the causes of such devastation must be investigated and then the danger zones must be identified. The causes are:

(a) The climate.
(b) The oro-hydrographical situation. The different topographical maps, forest maps and irrigation maps give a clear picture of the country concerned.
(c) The geological situation. This is shown on the different geological maps.
(d) The soil. Only small-scale maps (1 : 250,000 and sometimes 1 : 100,000) are available. Detailed maps do not exist.
(e) The land use and covering of the soil. The aerial photographs give a clear picture of land use and soil covering. Recent vertical aerial photographs from Java are available only for a very small part of the country. Photographs of the year 1946 (scale 1 : 50,000) exist for the whole island of Java.
(f) The different maps drawn from the aerial photographs show the danger zones and spots.

5. With the aid of the maps and photographs a basic map can be drawn showing where the danger areas and spots are found. Two graduates in forestry from the Agricultural Faculty of the Gadjah Mada University have already prepared such a basic map.
6. Control of land deterioration can be outlined with the aid of these basic maps.

It must be mentioned that the deltas of the rivers Brantas and Bengawan Solo could not be investigated because they are situated in a defence area, and that the river Tarum has already been investigated by Dr. Verstappen.

Résumé

L'expansion des deltas dans l'île de Java (F. Hollerwöger). *Résumé* par Iso Reksohadiprodjo.

Afin d'éviter tout malentendu, il convient de signaler que, dans le présent résumé, le terme « érosion » désigne l'altération des sols (agricoles) dans les bassins de ces fleuves sous l'effet de la déforestation des pentes montagneuses.

Pour sa part, M. Hollerwöger juge impossible de calculer l'expansion de ces deltas, car, dit-il, « nous ne savons pas combien de sédiments sont déposés dans la mer ».

Par ailleurs l'auteur du présent résumé soutient qu'il est possible, et justifié, de déterminer l'expansion de ces deltas au moyen de calculs « planimétriques » et, grâce à la courtoisie du professeur Ali Djojohadinoto, de Bandung, il est en mesure de présenter dans l'introduction le résultat de ces opérations complexes.

Dans presque tous les deltas étudiés, l'expansion annuelle moyenne s'est accrue considérablement au cours des vingt-cinq dernières années. C'est assurément là un symptôme grave et inquiétant qui requiert une étude encore plus poussée du déplacement des cultures et engage à neutraliser ses effets néfastes dans plusieurs « régions critiques » (c'est-à-dire la déforestation massive des régions montagneuses.)

Discussion

H. T. VERSTAPPEN. Planimetric analysis of delta growth is not satisfactory in every case because when the deltas, during their outward growth, reach seas of greater depth, the accretion will slow down. Depth contour will then provide a means of volume estimation.

A considerable increase in recent (± 100 years) delta growth is evident in northern Java. If we use the present as a starting point for our calculations the astonishing result is obtained that the whole alluvial plain has been formed in approximately 2,000 years, whereas it is evident that the formation started approximately 5,000 years ago when the maximum post-glacial sea level was reached. It is thus evident that accretion of the low land increased by two or two-and-a-half times and that erosion in the upstream part of these river basins occurs at present, due to human interference in the natural environment.

F. R. FOSBERG. In the paper read by Professor Iso Reksohadiprodjo we are dealing with two phenomena: the first, emphasized quite rightly by the speaker, is the serious denudation and soil erosion of the upland, and the other the accretion of the products in the growth of the delta. The latter is an example of the beneficial effects of erosion so often, perhaps facetiously, referred to by Professor Sir Dudley Stamp. He considers erosion a beneficial process so long as the products are collected and utilized. This is presumably an example of such collection and use. Incidentally, the accretion of silt on delta lands and consequent increase in soil fertility is obviously another such example.

Hydrological achievements and social problems

J. D. N. Versluys

In concentrating on the many technical problems connected with large irrigation projects, the engineer may become so deeply involved that he could forget the actual purpose of the work: to serve the population for whom the project is meant. It may be useful to draw attention to some problems of a quite different nature from the technical ones with which the hydrologist is familiar, but which are so vitally important that if left unsolved they may completely undo the beneficial effect of the project on the development of the economy.

It may be asked how far the hydrologist and the engineer are really concerned with problems not immediately belonging to their specific sphere of interest. Should it not be the economist and the sociologist who take care of matters extraneous to the technical aspects of the project? The answer would seem to be that, although economic and social matters should obviously be the responsibility of the specialists concerned, a project is a whole and should be planned also in its purely technical aspects, with a view to the place it will take in the social reality. It may be useful to illustrate this with an example derived from personal information kindly provided by Mr. C. Op't Land, a sociologist who carried out research in the area concerned where he has been living for about three years.

The project was planned for one of the largest deltas of Asia and conceived as one gigantic master plan, embracing the whole of the delta or approximately a surface of 1 million hectares. The reasons for this decision were largely technological although financial reasons were also offered in terms of the benefits which would be derived by the national budget. "This calculation was made, although many data were insufficiently known and while similar calculations on lower levels of economic activity (like region, district and the average farming unit) were omitted. It moreover assumed that farmers and farms could be adapted to the new production condition without extra cost and other adjustments in the region (reparcellation, restructuration of village sites and road system, administrative adjustments, etc.) were not envisaged. It was also assumed that the local farmers would spontaneously know how to use effectively the new possibilities of production offered by the scheme."

Indeed, the authors of the plan were well aware that considerable research should be made before their preliminary draft could be prepared in its final form. Some of the topics they recommended for further study were actually of a social nature, but it was taken for granted that the farmers would adapt themselves and their agricultural methods and techniques to the project, without considering the possibility of adapting the project to the people. Mr. Op't Land writes: "For one thing, the technical apparatus would merge a heterogeneous and not integrated region and its population, forcing them to create the necessary organizations of maintenance, operation and control. And . . . there were none before whatsoever. For all practical matters and for every conceivable purpose they fell asunder in a host of autonomous units. Irrigation, by which I understand the controlled supply and drainage of water and its efficient distribution, is not practised within the area. The need to supply water to plots has never given occasion to co-operation. Neither does any other agricultural activity. . . . As it is, the project consists of hundreds of elementary irrigation blocks, all taking their water from a tertiary channel. The size of these blocks would be from 500 to 800 acres. Land parcellation being as it is, this datam implies that up to 8,000 plots (and possibly as many individual farms) would have to be organized to effectuate efficient irrigation." The farmers would have to carry heavy responsibilities. "They would have to organize supervision and control of irrigation discipline, fixing of the watering schedules on a round-the-clock rotation basis with fixed timings and water quantities. Especially the nightly periods would be hard to enforce and to control. Not only that but virtually all agricultural activities would have to be

synchronized to maximize profits, and crops (brands and types) would have to be standardized."

The basic difficulty was that the population concerned was not accustomed to this type of agriculture requiring a high level of organizational ability, including the authority to enforce the rules. Here we have to think, for instance, of the problem of the connexions between the tertiary canals and the actual plots to be irrigated, of levelling the fields, of drainage, etc., which make up the complicated network of a large irrigated area and require constant attention and supervision to make the intricate system work.

It is clear that in areas where there is an age-old tradition of wet paddy cultivation such big irrigation projects would have a far better chance of success, but even in such areas it would be important to see how far the new irrigational units would fit into the existing structure. Close co-operation between the technical and social experts would be required to conceive the project in such a way as to achieve its real purpose: the economic improvements the population needs and for which the social preconditions of willingness and ability to co-operate purposefully should—if not present already—be carefully taught and encouraged. And it is clear that a project which can be broken down into small units will have the best chances unless the population concerned already shows a high level of ability to co-operate in such matters. A striking example is the *subak* system in Bali, a traditional social structure differing from that of the village and based on the irrigational unit. But such a system and the ensuing organizational abilities were lacking in the area mentioned above, resulting in grave danger for the success of the project as a whole and a serious risk of very heavy losses.

In quite a different way, social problems may have to be envisaged in irrigation projects. When an artificial lake is to be created, it is obviously necessary to remove the population—sparse though it will usually be—from the area and to provide new settlements. Similarly, in many cases newly irrigated areas have to attract settlers to cultivate the land which now provides possibilities of intensive agricultural exploitation. The ultimate success of the project will largely depend on the way in which the organizers have conceived and solved the various problems inherent in such settlements.

Here again the social and economic problems tie up with those of engineering and hydrology. Let us take some projects in Ceylon as an example.[1] The first large-scale settlement area at Minneriya (central Ceylon) was started as early as 1933 but received its real impetus after the war when through the use of DDT it was possible to protect the settlers against malaria. Irrigation canals could use the existing "tanks" or ponds and the main problem was the clearing and levelling of the land. Settlers were recruited from all over the country, mainly landless farmers with large families so that there would be sufficient manpower to cultivate the area, also in the future. The pattern of settlement was such that each family was given a neat brick house constructed on one of his plots, which consisted of 5 acres of irrigated land and 3 acres of dry land. They also received, free of charge, two buffaloes, farm implements, a small monthly allowance during the first six months and 600 rupees ($125) to bring the land under cultivation. The total cost per family amounted to 15,000 rupees (approx. $4,000), including the expenditure on clearing and preparing the land.

The results were satisfactory in many respects since the farmers secured a much higher income than they had in their previous village, but the system of settlement showed some clear deficiencies as well: (a) the old villages around the project saw with some envy the many benefits strewn on the newcomers whilst they had only disadvantages, especially those caused through the drainage water coming from the project plots damaging their own fields; (b) since each family was living on its own plot and no attention was paid to its social or geographical background, there was no feeling of community which could have resulted in mutual help and therefore more efficient use of manpower; (c) the settlers were so well looked after by the government that they were neither inclined to take any initiative themselves nor to co-operate to achieve better results; (d) the surface of land was actually too large for one family. Here we see that the physical planning had a decisive influence on the actual social and economic effect of the scheme.

The lessons learnt at Minneriya benefited the large Gal Oya project taking its first settlers in 1951: the homesteads were built rather closely together on dry land and located so as not to oblige the farmers to cover more than 1½ miles to reach their fields which were somewhat smaller than at Minneriya, and farmers from one district were grouped together which favoured the establishment of co-operation and of community spirit. Each village had a village officer to help the farmers, to manage the village co-operative and, in general, to act as the liaison man between the village people and the various government services. This indeed helped to overcome the difficulties experienced in the other project.

The actual layout of the houses and of the village is an equally important matter to be considered by those planning new settlements, since the settlers should feel at home in their new surroundings. Failing to do so may result in serious losses, as were experienced in a large Indian project where the first village neatly built by the project engineers was so little to the liking of the would-be settlers that they preferred to build their own homes.

The latter method was systematically followed in the Indonesian "transmigration" scheme (settling farmers from over-populated Java in sparsely populated Suma-

1. For a more complete discussion see J. D. N. Versluys, "The Settlement of Landless Farmers in Some Asian Countries," in *Indian Yearbook of International Affairs*, Madras, 1956.

tra). Far more was left there to the colonizers themselves, even most of the clearing and preparing of the land. Although this makes the total cost much lower, the obvious disadvantage is that the whole process of resettlement is much slower and this method can only be followed when the settlers have a thorough experience of wet paddy cultivation.

Once again, the details of the social and economic aspects of the project should clearly be left to specialists in this field, but the hydrologists and engineers should be well aware of the existence of such problems. They should make sure that well-qualified people are taking them in hand and be willing to co-operate closely with the economists, sociologists and agricultural extension officers connected with the project. It is particularly important that the timing of the social preparations is such that they will start early enough to be of real benefit. The co-operation should therefore start right at the planning stage and continue throughout the execution of the project. This may not solve all the problems, but it is certain that in this way the chances of success are better. As David Mandelbaum put it, the advice of social scientists "may do no more than point out what specific information and what theoretical formulations are needed to approach a solution. But this in itself will serve the goals of the development planners whose aims of better food and health and living conditions are frequently undermined by haphazard notions of dealing with social matters, which they use in their plans".[1]

1. David C. Mandelbaum, "Planning and Social Change in India," *Human Organization*, Vol. 12, No. 3 (Fall 1953).

Résumé

Travaux hydrologiques et problèmes sociaux (J. D. N. Versluys)

Il existe, à côté des problèmes techniques qui sont directement de la compétence de l'hydrologue, d'autres problèmes d'ordre social, économique, psychologique, etc., dont l'importance est telle que, si on les ignore, on risque de réduire à néant les effets bienfaisants que le projet peut avoir sur le développement de la société.

Si ces problèmes sont évidemment du ressort des spécialistes — l'économiste, le sociologue et l'anthropologue — l'ingénieur ne saurait raisonnablement s'en désintéresser car tout projet constitue un ensemble et, même du point de vue purement technique, il doit être conçu en fonction de la place qu'il occupera dans la réalité sociale où il est appelé à s'implanter. A titre d'exemple : un projet devait être réalisé dans l'un des plus grands deltas d'Asie; il avait été conçu comme un vaste plan qui engloberait l'ensemble du delta, soit approximativement une surface d'un million d'hectares. La décision avait été prise surtout pour des raisons techniques bien que des raisons financières eussent également joué leur rôle. On supposait que les agriculteurs et les exploitations pourraient s'adapter aux nouvelles conditions de production sans grandes difficultés. On supposait également que les agriculteurs locaux sauraient d'instinct utiliser efficacement les nouvelles possibilités de production offertes par le projet. On considérait comme un fait acquis que les fermiers allaient s'adapter et adapter leurs méthodes et techniques agricoles au projet, et l'on n'envisageait aucunement la possibilité d'adapter le projet à la population. Le projet devait agglomérer une population hétérogène et éparse en la forçant à créer les dispositifs nécessaires d'entretien, de fonctionnement et de contrôle... Rien de ce genre n'avait existé jusqu'alors. Or, en fait, ces conditions et bien d'autres n'étaient pas réunies et le projet connut les plus graves difficultés.

Une deuxième catégorie d'exemples montre l'importance de la planification physique des villages dans des territoires nouvellement développés.

Un projet cingalais, celui de Minneriya, fut généralement bien planifié et connut un succès certain. Quelques faiblesses de conception ont servi de leçon aux organisateurs du projet de Gal Oya (également à Ceylan), où les premiers colons se sont établis en 1951 : les fermes ont été construites assez près l'une de l'autre; on groupa les fermiers d'un même district de façon à favoriser l'esprit de coopération et le sentiment communautaire qui manquaient à Minneriya. Dans chaque village on désigna un responsable chargé d'aider les cultivateurs, de gérer la coopérative et, de façon générale, d'assurer la liaison entre les habitants du village et les divers services de l'administration.

Methodology in area analysis[1]

N. Crain,

INTRODUCTION

With a few significant exceptions, advance area planning in modern countries is relatively new. Until the 1930's even the most highly developed industrial countries frequently provided no lead time for area development. Indeed, area development tended to "just happen". It is fortunate that, in most of the highly developed industrial areas of the world, population pressure on the land was relatively light; and as industrial urban societies developed, the strain on the natural resources, especially land itself, was relatively slight.

In the urban centres, the pressures that developed, especially in Europe, were such that planning from the standpoint of geometric design developed rather early. Paris, for example, emerged after about 1800 with a definite plan of street layout based in part, it is true, on political considerations so that mobs could be stopped without getting a full sweep of broad boulevards. Other cities were designed from the start, such as Washington, D.C., in the United States, and Brasilia, in Brazil. Still others were rebuilt following catastrophes, such as the London fire and the Tokyo earthquake. But it is only in the last few decades that many countries have assumed the responsibility for promoting the development or reclamation of large areas of non-urban landscape. In many cases, these areas already are developed in the sense that they are being used. Frequently, the pressure on the land is already great, and so is the demand on the resources available at the time. Thus, when this type of development is planned, it is not starting with a simple, unpopulated, uncomplicated landscape upon which can be superimposed whatever plan is desired Instead, the development of such areas is manifestly more complicated than the planned development of less populated or less well-developed areas. The problems of changing land tenure, dislocating people, threatening taboos and modifying deeply rooted cultural patterns are all more complex and difficult than the problem of changing the contour of the land or the drainage of streams.

While by no means the first of the planned developments, the successful establishment of the Tennessee Valley Authority (TVA) in the United States became the inspiration and model for the idea that over-all development of a region might be successful even if it is already populated and even if vested interests are already firmly established. The TVA also demonstrated some of the advantages of a complete over-all master development plan for a region as against a piece-meal, hit-or-miss development of many small areas.

More recently the idea of being able to develop the wet tropical areas along the same general lines began to hold out much hope. There were many problems involved in attempting to implement such an idea. Capital availability, technical know-how, political and cultural stability all have had to develop before adequate planned development could be contemplated in many areas of the world. In addition, the skills required, not only to provide the engineering and construction necessary for modifying the physical environment, but even more important, the skills required to inventory the physical environment adequately so as to identify the significant elements as against the insignificant, and so as to develop a synthesis of the whole programme, were lacking. Furthermore, the sheer bulk of the information concerning any kind of truly complex area was so great that the handling, processing and evaluating of these data frequently were impossible in the past. Furthermore, the initiative and enthusiam required for any major change in the use of an area were often lacking, partly because it was necessary to depend upon foreign

1. For 15 years, members of the Department of Geography at the University of Denver have been engaged in regional development studies. In several cases, the department has had primary responsibility for the basic planning. This paper is a report on some of the methodologies which have been developed and represents the combined efforts of various members of the department. In addition, support from the Advanced Research Projects Agency has made possible some of the work.

technical skills. Not until indigenous skills were beginning to develop was the best use of the skills of foreigners within the framework of an indigenous plan possible.

Fortunately, much of the technical skill and know-how required for over-all planning were the result of experiences and education developed quite recently. I say fortunately, for this meant that no particular country or culture had a monopoly on these skills. Furthermore, since the Second World War, the interchange of students, almost throughout the world, has meant a very wide dissemination of knowledge of the new skills as they were developed. The result is that many of the skills involved in developmental planning lack a nationalistic or doctrinaire attachment and, therefore, not only are they more readily obtainable by people throughout the world, but they are more readily acceptable.

Today, then, people of all races, nationalities and cultures are concerned with the problem of the most efficient and effective way of using the resources they have. No longer is it really believed that one country should benefit by developing at the expense of another country.

In order to plan the development of any country for its own sake rather than to assist some other country, methods which will enhance the possibilities of success of the country doing the planning should be universally applicable.

SIGNIFICANCE

Any methodology involved in the development of an area must take into account the problems of inventory, for without a meaningful inventory of the resources of an area and an investigation of their relationships to one another and to the cultural development of the area, it is virtually impossible to formulate a meaningful plan for the development of this area. Many mistakes have been made in the past as a result of the unwillingness to recognize this essential. Many times there have been assumptions that a technical engineering survey of the engineering feasibility of the physical works needed in an area was all that was necessary. In fact, there is more to the development of an area than just the physical works involved. Many examples of failures exist which can be attributed to the engineering approach, although human nature is such that most of them do not get into the literature and are not widely known. In the United States, for example, several of the most highly lauded general reclamation programmes in developed areas have failed to develop economically as desired and in some cases have even failed to provide the resources that they were designed for.

On the other hand, it is impossible to measure everything about an area; and as a result, some generalizations in classifications are essential in order to be able to obtain the critical data without being overburdened with insignificant minutiae. Thus, it is helpful to classify the phenomena with which one has to deal in this kind of study (for example, by climate, terrain, vegetation, etc.) just as it is helpful to assemble the data within each classification into useful groups or relations.

The determination of the manner in which such phenomena should be grouped, as well as the determination of which phenomena should be stressed, comes as the result of two factors. It is sometimes difficult to determine which of the two factors is the more important. Probably they are of equal importance. One factor is the determination of scale and intensity. The second is the determination of significance.

There must always be a decision as to the practical limit within which one can work. It is essential to determine in advance the detail which can be handled, and which it is practical to provide, either by field-work or by other methods of data-gathering. Also, one must determine how intensely certain elements of the environment must be studied in order to give information which is meaningful, for this intensity may very well influence the determination of the scale to which maps, data collection, field operations, etc., can be pointed. This determination of scale is a very significant one, for if the presentation of data is made at, say, 1 : 50,000 in map scale, the detail of such items as terrain features will be generalized at fairly broad levels compared to the presentation of the same area at a scale of 1 : 10,000. Not only does the latter offer the opportunity of showing the features of the landscape at roughly five times the dimensions of the former, but the amount and detail of features also increase.

The other factor mentioned above which helps to determine the characteristics and type of planning is that of significance. Very simply, this means that the purposes, objectives, and anticipations of any proposed development must be determined in advance; for these elements are extremely important in determining the form, manner and intensity of information which must be accumulated in order to produce a good plan. The determination of what about the physical environment is significant in developing a plan is not always as easily arrived at as may at first appear. While many elements of the environment are obviously significant to whatever planning might be done, it is equally true that many of the elements which might not be immediately identified frequently will prove to be of extreme significance in so far as the specific objectives of the plan are concerned. Thus, the determination in advance of some of the areas of significance in terms of developing a meaningful set of inventory factors is essential. Also, in planning any kind of a reclamation or development programme, the development of sets of goals of different levels of progress and different alternatives must be determined —if possible, before the inventory of resources—so that the inventory can be pointed toward these goals.

The understanding of various alternative methods of development of an area, of course, is very important; for, unless it is determined in advance what alternatives

are acceptable, the determination of how the inventory information can be used may not be effective. Scientific and logical determination or choice between acceptable alternatives is a very important element in improving decision-making. But this scientific choice between alternatives is not possible unless the information on which such choices can be made is properly prepared and presented.

It should be emphasized again that determination of the objectives involved in the development of an area should be based upon practical consideration and should provide for some alternatives. In addition, however, there are certain dangers in the concept of development which are not always recognized. It should not be assumed in advance without other evidence that all-out development of one area can take the same form that it may have taken in another area or another country. Questions of national policy, availability of capital and the necessary skills and materials and social, cultural and religious factors all combine to modify objectives, goals and the level of development that should be established in a given area. The determination of the availability of capital and of the necessary skills and materials is partially a political decision, for when these skills and materials are not available locally, a national decision must be made as to whether or not they should be imported. Sometimes alternative objectives must be considered on the basis of the availability or non-availability of skills and materials. In any event, the actual development of a programme and plan should follow this determination of national policy and should be within the concepts thus determined. Only then can the alternatives and goals be arrived at with any hope of a successful decision as to alternatives and as to the level of development.

Once these determinations are made and the alternative goals have been determined, then it is possible to establish levels of intensity and scale in order to establish the kinds of information that will be needed in order to make careful and proper decisions.

THE ENVIRONMENT

So far as the study of the environment is concerned, it can be divided into three major areas: climate, vegetation and terrain. Some general considerations of these three fields are discussed in this section, and in the next section some of their characteristics are examined as well as the effects which they may have.

Climate

Of the several physical environment components, climate affects man's use of an area to perhaps the greatest extent; notably, though not exclusively, because of its influence on the food production capacity of the area. There are many ways to offset a troublesome climatic endowment, but permanent, economically-sound settlement of an area by a substantial population is strongly dependent, in the main, upon the area's ability to feed itself. Hence, a matter of primary concern to the planner should be the securing of as representative an image of climate as possible. Such fundamental considerations as possible land-use categories and proposed basic food crops depend significantly upon the kinds of climate and their amenability to modification toward man's purposes.

At least three lines of investigation may be followed in building a climate model for planning. A systematic survey of accomplished studies, summarization of their findings and organization of those findings into a usable picture compatible with the scale of the planned effort is a possible beginning point. An assessment of the data available should be a concomitant effort so that, as they become apparent, some of the gaps can be filled by studies done by the planning staff. As the combination of these two efforts begins to produce a skeletal picture of the area's climate, the opportunity to fill still existent critical gaps manifests itself and, where feasible and the needs of the project warrant, original data collection can be instituted. Despite the short-time records such installations will provide, these data, along with non-climatic evidence of climate, will afford some assistance in climatic boundary establishment. The use of analogues may also augment the utility of such sites where they can be realistically employed.

Climatic maps, however crude and imperfect during the initial stages of research on an area, may have utility. Such maps should always be recognized for what they are: hopefully, a series of consistently-improving progress reports; so long as they are kept out of unqualified hands, they may contribute to integration of effort. Even the map being used in the final stages of planning may leave much to be desired as to completeness, accuracy, etc., but the task without any such map is a harder one.

It hardly seems possible to overemphasize the importance of existent climatic data. Many aspects of these data deserve consideration, foremost among which are temporal and spatial coverage. It is important to know with what degree of certainty one can base plans on summarized climatic data, and length of record is basic to such certainty. Relative freedom from intra-annual time gaps in the record is but a subheading under length of record. Distances between stations with comparable record lengths, while important, may not be the significant factor; two stations may give an accurate picture of a 100-mile stretch of featureless plain, while four stations may inadequately represent a smaller but diverse area. Paucity of stations is a typical feature of many developing areas; hence, the more information that is available about each of the few stations, the better one can assess the reliability, representativeness and the like. Types and changes of instrumentation, movement of instrument sites, natural and/or man-made features surrounding the site

(wind-blocking effects of walls, trees, etc.) and changes in the amount of training of personnel are but a few reliability considerations. Knowledge of the form in which data are stored (punched cards, published tables, maps) makes planning for studies to be carried out more efficient.

Standard surface element coverage (precipitation, surface wind velocity and direction, cloudiness, ceiling, temperature, humidity, visibility, etc.) needs supplementing. Upper air data forms (as available through Radiosonde and Rawinsonde) may be useful; more sophisticated and current forms may be necessary for selected localities. Data from stream gauging stations, from evapotranspirimeters, and from rain gauges will be necessary for flood control, water storage for irrigation and power, and other development planning, annual as well as seasonal. Every effort should be made to secure hourly data as well as daily, monthly, seasonal, and annual data. A representative depiction of precipitation is hardly possible without some expression of intensity; some locations receive more than half their annual rainfall during a few hard rains, each lasting only hours. Depending upon the nature of the physical setting, expressions of human response such as wind chill and discomfort index or sensible temperature should be instructive. Additionally, selected combinations of elements will prove useful for some types of planning (wind direction and visibility, wind direction and velocity, precipitation and wind).

Lastly, some comment on the form of data treatment may be appropriate. There is an almost endless variety of treatments to which a fairly complete set of climatic data can be subjected. The availability of data in an underdeveloped area will exert a limiting effect on such treatments from the practical standpoint, and the purpose of the project will further limit the number and variety of treatments from the standpoint of scale. To the extent that it is possible, however, data treatment and expression should reveal amount and frequency of deviation from average conditions as well as the averages themselves. Only with such indicators will appropriate selection of alternative lines of development be most effective.

Vegetation

Before planning to develop an area, it is imperative that a thorough knowledge of the existing vegetation, both the natural species and those under human influence, be obtained. The vegetation may affect development plans directly (e.g., agriculture or timber production plans) or indirectly (e.g., flood control or transportation effects). The inventory should include the distribution and the amounts of land under human use and land relatively undisturbed by humans. The land under human use should be classified as forest (e.g., timber plantations, rubber plantations, etc.); grazing, including forage crop areas and native vegetation; under cultivation, with a breakdown into the major crops. The land which is relatively undisturbed by humans should be considered in three main groups: the forest vegetation, the brush or scrub vegetation, and the herbaceous vegetation. Each of these groups should include an inventory of the main vegetation types.

Besides knowing the areal extent and distribution of each vegetation type, it is also important to have a more detailed inventory of the composition and characteristics of each. This would provide information to assist in constructing management plans or to use as an indicator of site potential. The information to be obtained in such an inventory would vary with the vegetation type and with the development scheme. However, in all cases, the spatial arrangement, both in the horizontal and vertical planes, is of primary importance. When the vegetation is to be utilized, it is also important to determine the species composition since species vary, for example, in timber value, palatability, etc.

In "developing" a region, it is important that one or several areas be set aside as natural areas or preserves. This provides the land management specialist with a standard against which he can measure his management practices. It also provides the scientist with a permanent place to carry on research in the natural sciences and the teacher with an excellent outdoor laboratory for training students. Although it may be of no immediate economic significance, a natural area also provides a place in which native plant and animal species might be protected from extermination and possible extinction.

Terrain

In regional development, terrain is particularly important in the location and improvement of surface transportation, dams and reservoirs, urban settlement, and potential agricultural lands. As mentioned before, some general notions about the possible uses for any particular area must already have been arrived at, upon the basis of governmental policy, availability of capital, etc., before terrain comes into consideration.

In the gathering of terrain data, several important items should be considered initially. The first concerns the intensity and scale of the data to be gathered. This in turn depends upon the degree of terrain homogeneity and the use to which the area may be put. If, for example, an ill-drained region is being contemplated for reclamation, an extensive soil survey should be undertaken to determine the largest possible area of fertile soil to be included in the project; while a far more intensive soil survey should determine the distance between surface drainage ditches and the optimum size of land holdings.

Secondly, an alternative land use should always be considered where local environmental features rule out the primary use. For example, the primary objective

for the drainage of the Ost-Flevoland in the Netherlands was to increase the area of arable land; however, an intensive soil survey indicated that the western portion of the polder was composed of very sandy soils which would be better suited for the location of an urban centre rather than for farm units. Consequently, the sandy site is now being developed into Lelystad, a future city of 30,000 population.

Following the general considerations above, terrain analysis calls for the gathering and analysis of data on terrain factors of surface geometry, surface materials and hydrology.

Surface geometry is physical forms or shapes that comprise the earth's surface and their interrelationships. For all types of area analysis studies, many components of the earth's surface geometry need to be measured and described, including pattern, profile, slope, elevation, texture, grain and relative relief. Of particular importance is slope, for many environmental characteristics, such as soil quality, agricultural potential and location of transportation lines, are dependent upon the slope of the land. Land slopes up to about three degrees, other things being equal, are the most valuable for agricultural and other purposes. The well-drained flat or nearly flat lands of the world have the densest populations, the cheapest transportation lines and the most profitable agricultural production.

The second factor of terrain, surface materials, concerns the physical properties and attributes of the earth's mantle and bedrock, as well as the changes which occur under differing conditions of moisture. Many features of mantle material need measurement and evaluation, such as soil texture, structure, compactability, permeability, productivity, and strength. Similarly, information of the bedrock should be gathered, such as genesis, structure, permeability, depth and strength.

Hydrology, the third feature of terrain, must always be considered in the planning to develop an area. The use of water for irrigation, domestic needs, navigation and power, or its regularization to prevent flooding, demands the gathering of information on hydrology. Of importance are data about the size, shape, distribution and quality of water bodies, as well as about currents, velocity, frequency and duration of flooding, water purity and composition of stream banks and bottoms. In many respects, hydrological studies form the most difficult part of terrain analysis because of the possibly great annual and secular fluctuations of stream flow, which in turn depend upon rainfall amount and intensity as well as the character and condition of vegetation.

After the gathering and mapping of information on these elements of the terrain, regional developers would be wise, whenever possible, to compare their area with already developed areas of the world which have like or similar terrain features. Thus, it should be possible to test the suitability of particular land uses for the terrain under examination measured against previous experience.

ENVIRONMENTAL FEATURES AND CHARACTERISTICS

The physical environment of any area which is subject to study can be thought of as composed of features whose details may be described in terms of their characteristics. In this sense, features are those portions of the physical environment of an area to which we can ascribe some unity. They need not have precise boundaries nor exact forms, but they should have sufficient conformity to allow for this unity. Hills would be an example of features, as are valleys; and it is obvious that no one can say precisely where one stops and the other begins. Still other examples of features could include leaves, raindrops, clouds, winds, lightning flashes, insects, mammals, roads, houses, grains of sand, etc. While some of these are not exactly features of the physical environment, they are features of the landscape. Features, therefore, are objects, events or groups of objects or events which are identifiable in the landscape and which are subject to description. Such description is in terms of their characteristics, and it will be modified considerably by the types of characteristics which are significant to the ultimate user.

The characteristics of the environment are not features in themselves, but are simply means of describing the features. Colour, duration, intensity, slope, palatability, elevation are some examples of characteristics of features of the landscape. They are all attributes of features. Some characteristics may easily be quantified (such as elevation or length) and as such lend themselves to very precise measurement and precise recording systems. Others (such as palatability or aggressiveness) do not lend themselves readily to quantification and, therefore, have to be dealt with in a different fashion. An example quoted from a recent study in the Department of Geography at the University of Denver will indicate the differences: "Although the plateau's highest point reaches 3,216 metres, its average elevation is about 2,400 metres above sea level."

In this illustration, both the plateau and the highest point are features of the landscape, while elevation is a characteristic of these features. The two quantities, 3,216 metres and 2,400 metres, can be thought of as parameters, which in this sense, are used as a mathematical index of a characteristic. Environmental analysis is primarily concerned with characteristics and their parameters, rather than the actual features themselves, and the careful identification of the significant characteristics with their parameters becomes a critical factor in any procedural method. There is no definite rule which can be relied upon to establish significance of characteristics of the physical environment.

The objectives of the proposed plan and the design of the problem are, however, criteria for judging which of the many characteristics will be significant. Relating environmental characteristics or conditions to the effects or changes proposed will assist in the determination of significance.

However, there is an inherent obstacle which is the problem of evaluating the effects produced by changes in the environment. The matching of a characteristic or group of characteristics with an item of equipment, or a particular irrigation activity, or groups of cultural activities assumes that the individual doing the matching is competent to evaluate the effect. This is, however, a sweeping, and I might be so bold as to say, primarily erroneous, assumption. Basically, the environmentalist who may be able to define leaf colour and carbon dioxide concentration in the air, as well as soil composition and rate of run-off, may not, however, be competent to judge the effects of these conditions on the potential development of an area. Even assuming that he knows all that is necessary to know about objectives and limits of development, as well as what kinds of engineering competence are available, he still is not in a good position to judge completely the effects of these conditions on the plan. Such type of matching would assume that the evaluator combines in one person the qualities and capabilities of both the environmental specialist and the economic planner. There are few, if any, individuals so qualified.

Since there are only a few components of any developmental plan, it is possible to identify the over-all effects produced by specific changes in environmental conditions in terms of the three components: people, places and things.

The component "people" will include not only effects on persons, but also those upon their activities or functions. "Places" will include all of the physical elements of the landscape, while "things" will comprise equipment, installations and supplies; all of man's possessions which are present in the landscape. Any change of environmental conditions may have an effect upon one or all of the three components. In identifying the effects, we lay the basis of a good developmental plan.

While there are infinitely large numbers of distinguishable environmental characteristics and similarly large numbers of items and activities, there are actually relatively few possible effects that such environmental characteristics can have on the development of an area. For instance, all supplies, equipment, and installations consist of matter; and there are only a few fundamental ways in which matter may be affected or changed. Similarly, all components in which movements are concerned can be affected in only four ways: that is, by changing direction, rate, payload, or amount of energy required. Also, while there are numerous ways in which personnel may be affected by environmental characteristics, these mostly can be limited to a few significant effects. Such effects on people, for example, can be classed as psychological, physiological and physical. Psychological effects of the environment include all ways in which the mind is influenced; physiological effects are those in which bodily functions are changed in some manner not involving injury; and physical effects are those in which there is a probability of induction of some form of physical trauma or damage.

In the case of supplies, materials, equipment and installations, the number of ways in which changes in environmental characteristics can produce significant effects also is limited. Examples are changes in the structural utility of a feature; change in the probability of physical, chemical or biological damage to equipment. Similarly, effects upon domestic animals and livestock can be identified.

Using the same logic, it is possible to define the effects which can be produced upon activities or functions that are carried on. Such functions are transportation, energy transmission, storage, etc. Whatever the activities may be which are desired in the planning of the development of an area, such as dairy farming, commercial agriculture, fibre production, etc., they can be included in such a classification. Thus, changes in the physical environmental characteristics which may be brought about by any engineering development can be identified even in these cases, and the resulting effects be determined.

ILLUSTRATIVE EXAMPLE

As an illustration of the procedure, but definitely not an example of such a study, the diagram of a "matrix" is presented (Fig. 1).[1] Across the top are listed some representative effects on people, places and things which may result from changed environmental conditions. Down the side of the diagram are a few examples of changed environmental conditions. For ease in reading, these have been grouped under the headings of climate, soil, terrain, flora and fauna, and cultural features. Let me emphasize that there is no record of how the change is made, only a statement of what condition of the environment has been altered. Nor is there any implication of quantity or degree of change.

This hypothetical study has a three-element relationship expressed between the components and the changes. Some changes obviously have a definite effect, which is indicated by the sign ● for "yes". Other changes have no discernable effect, and the relationship is indicated by a blank opposite the items. For some changed conditions, we may be uncertain of the effects, so the sign O is inserted for "maybe". As you see, almost one-half of the indications are in doubt. These are the relationships which must be

1. In addition to Figure 1, an appendix has been included as an example of a possible check list to aid in the gathering of graphic data about any country.

Effects—change produced in:	*People*									*Land*							*Equipment and installations*						These effects ← are caused by these changes ↓ Changes in environmental conditions
	1 Mental efficiency	2 Ease or effectiveness of respiration	3 Probability of infection	4 Probability of toxic reaction	5 Probability of induction of physical trauma	6 Probability of exhaustion or fatigue	7 Eating habits	8 Food requirements or availability	9 Drink requirements or availability	1 Structural utility of a feature	2 Depth to water table	3 Availability of surface water	4 Soil fertility	5 Soil minerals	6 Rate of percolation	7 Rate of run-off	1 Structural utility	2 Rate of movement	3 Direction of movement	4 Energy requirements or availability for movement	5 Size or weight of payload of transport	6 Availability and type of water transport	
																							Climate
	●	●	●	●	○	○	○	○	○				○	○	○	○	●	○					1 Add pollutants to atmosphere
	○	○	○	○				○	○		○	○		○	○	○	○	○	○		○	○	2 Seed clouds
	○	○	○	○		○		○	○		○	○			○	○	●						3 Modify humidity
																							Soil
						●	○	●		●	○		●	●	●	●							1 Modify methods of cultivation
						●		●		●	○	○			○	○	●	●	○	○	○		2 Stabilize surface materials
																							Terrain
								●	○	●	○	○	●	●	●	●		○	○	○	○	○	1 Modify erosion
								●	○	●	○	○	●	●	●	●		○	○	○	○	○	2 Modify deposition
			○					○	○	●	○	○			○	●		●	●	●	●	○	3 Modify surface shapes
	○		●	●			○	○	●			●	○	○	○		●	○		○	○		4 Add pollutants to water
																							Flora and fauna
		○	○	○	○	○	●	●	○	○	○	○	○	○	○	○		●	●	●	●	○	1 Modify native species
		○	○	○	○	○	●	●	○	○	○	○	○	○	○	○		○	○	○	○	○	2 Introduce new species
			○	○			○	○	○	●	○	○	○	○	○	○		○	○	○	○		3 Add windbreaks
																							Cultural features
			○	○			○	○	○	●	●	●		○			●	○	○	○	○	○	1 Divert water
							○	○		●	○	○	○	○	○	○	○	○	○	○	○		2 Divert cropland
	○		○		○		○	●	○	●	○	○	○		○	○	●	●	○	○	●	●	3 Improve transportation facilities
			○	○			○	○	○	●	○	●			○	○	●	○	○	○	○	●	4 Impound water

FIG. 1. A sample of a matrix study (these are incomplete listings). Key: ● = yes ○ = maybe blank = no

carefully examined to ensure the plan does not produce new hazards or undesirable results. Study of the "yeses" and "noes" will determine if the proposed plan will actually produce the changes for which it was designed.

The illustration is but a miniature of the matrix which would be necessary for the complete study of a plan. Every significant item from the resource inventory must be investigated and matched against each change which will be produced by the developmental plan. The extent and complexity of a complete study may require reliance on machine programming for the sorting and matching of components and environmental conditions. Only by this complete analysis can the benefits and drawbacks of a proposal be determined.

APPENDIX

SECOND PRELIMINARY LIST OF DESIRED STANDARD GRAPHIC COVERAGE FOR ANY POLITICAL OR PHYSICAL UNIT [1]

1. Aerial photography
   (a) Coverage (obtain photo flight plan, index sheet, or maps).
   (b) Type (vertical, trimetrigon, oblique, etc.).
   (c) Scale altitude and camera focal length; preferably 1 : 20,000 for spot photographs and 1 : 12,500 or 1 : 10,000 where available (1 : 40,000 would be minimum).
   (d) Date.
   (e) Photographing agency and availability.
   (f) Purpose for which photography was used (mapping, road survey, forest inventory, etc.).
   (g) Interpretation studies of photographs.
2. Topographic mapping
   (a) Coverage (obtain map or index sheet).
   (b) Scale (preferably at least 1 : 50,000); projection and co-ordinate system; method of portraying relief.
   (c) Date.
   (d) Producing agency.
   (e) Means of preparation (controlled photo mosaic, multiplex, plane table); legend.
   (f) Type and intensity of geodetic control.
   (g) Planimetric map coverage where no topographic mapping exists.
   (h) Reliability of slope analysis (from cross-sections).
   (i) Language.
3. Other map coverage
   (a) Coverage (transportation, drainage, settlement, etc.).
   (b) Scale (1 : 250,000 to 1 : 1,000,000 usually adequate) and date.
   (c) Agencies and availability.
   (d) Reliability.
   (e) Geologic mapping; purpose and reliability.
   (f) Language; legend; colour scales.
4. Soil classification
   (a) Coverage (area and type, i.e., maps or symbols).
   (b) Scale.
   (c) Date.
   (d) Producing agency.
   (e) Means of preparation (use of aerial photographs, chemical analysis, physical analysis, etc.).
   (f) Soil legend and text materials (collect or duplicate); colour scales.
   (g) Evaluation of usefulness for agricultural planning and development (opinion of local map users).
   (h) Evaluation of usefulness for engineering (including trafficability) planning.
5. Land use
   (a) Coverage (area and type, i.e., maps or tables).
   (b) Scale.
   (c) Legend and text materials—criterion.
   (d) Classification methods and reliability of generalities.
   (e) Date.
   (f) Producing agency.
   (g) Purpose.
   (h) Means of preparation.
   (i) Comparison with United States Bureau of Reclamation standard land-use types.
   (j) Language
6. Ecology-vegetation mapping (also forest and pasture mapping).
   (a) Coverage.
   (b) Scale and reliability.
   (c) Producing agency, or individual, and dates.
   (d) Classification schemes used; legend; colour scales.
   (e) Taxonomic lists and pictures.
   (f) Scales of measurement and mensuration methods.
   (g) Language.
7. Climatic data.
   (a) Location of individual stations and relation to vegetation and settlement; altitude and exposure.
   (b) Period of record and continuity.
   (c) Types of data recorded, time spans.
   (d) Reliability; direct observation of recording instruments; estimates of extrapolation.
8. Stream-flow data
   (a) Location of individual stations.
   (b) Period of record.
   (c) Type of data recorded.
   (d) Watershed data.
   (e) Locations and data on dams; power stations; locks, etc.
   (f) Depth, width, variability, etc., on channels, together with dockage, fuelling, and other facilities.
   (g) Reliability.
9. Ground-water data
   (a) Map coverage, if any, of areas where investigations have been made.
   (b) Location of wells (wells per unit-area); extent of use; reliability and extent of reliance.
   (c) Depths and types of strata.
   (d) Extent of artesian pressure.
   (e) Types of records, both for flow and core.
   (f) Fluctuation measurements.
   (g) Quality measurements.
10. Ground photographs
    (a) Location of station.
    (b) Direction in which taken.
    (c) Type of description available.
    (d) Source.
    (e) Date.
    (f) Availability of prints.
11. Miscellaneous
    (a) Special economic and demographic maps.
    (b) Atlases covering: physical, cultural, economic, resource, communication, ethnic, power grid conditions, etc.
    (c) Glossaries of terms used locally concerning any aspect of the environment.
    (d) Indexes of graphic and other compiled data on environment.

1. Developed by Project DUTY from various sources and original research under Contract DA-31-124-ARO(D)-76, Department of Geography, University of Denver, August 1963. Prepared in the Department of Geography, University of Denver, with funds supplied by a Graduate College Research Grant, the Chancellor's Venture Fund and ARPA.

Résumé

Méthodologie de l'analyse d'une région (N. Crain)

Avec les techniques modernes qui permettent de traiter de grandes quantités de données, il est désormais possible d'avoir un inventaire circonstancié des ressources d'une zone dont on organise le développement. Il n'est plus nécessaire de s'en remettre entièrement à une sorte de connaissance intuitive de ce qui constitue la base des ressources.

La simple énumération des ressources d'une région ne suffit pas. Il est indispensable d'inventorier les ressources physiques d'une région de manière à pouvoir les analyser. Cette analyse faite, on pourra élaborer un plan de développement qui sera non seulement compatible avec la politique nationale, les ressources financières et les compétences dont on dispose, mais encore avec le milieu naturel fondamental de la région intéressée. Les échecs de certains grands projets de développement, qui n'ont pas donné les résultats désirés, notamment en agriculture, semblent dus en partie à l'absence d'une analyse de ce genre.

Afin d'utiliser au mieux l'équipement électronique moderne, tout comme les connaissances technologiques actuelles, nous présentons une méthode théorique, dont l'emploi pourra fournir les données nécessaires pour l'inventaire d'une région, sous une forme et à un degré d'intensité qui en permettront l'analyse soit par des moyens électroniques, soit par des moyens mécaniques.

Pour y parvenir, on a mis au point une étude du milieu qui part du principe que tous les éléments du milieu physique d'un lieu quelconque peuvent s'intégrer dans une liste de caractéristiques. On suppose que tous les aspects du milieu physique d'une région, sans exception, peuvent être réduits à ces caractéristiques. En outre, il est possible, pour chaque caractéristique, de définir les effets d'une modification qu'elle pourra subir. Par exemple, si l'angle d'une pente est modifié, cette modification peut affecter les transports dans quatre de leurs éléments : direction, rythme, prix ou énergie requise. La modification de la pente peut entraîner la modification d'un ou de plusieurs de ces quatre facteurs, mais elle ne peut affecter d'aucune autre manière les transports.

Portée jusqu'à sa conclusion logique, cette méthodologie permet d'analyser le milieu physique d'une région d'après l'utilisation que l'on veut faire de cette région. Si l'on procède soigneusement, on pourra étudier à l'avance des résultats de n'importe quelle modification du milieu. Le planificateur jouira ainsi de ce luxe indispensable de pouvoir choisir entre différents plans en se fondant sur des résultats prévisibles.

VI

Descriptive studies

Études descriptives

The deltaic area of the Irrawaddy river in Burma

A. Volker

The deltaic area of the Irrawaddy in Burma (Fig. 1) offers a typical example of a delta in a humid tropical zone in an early stage of hydraulic and agricultural development. It is one of the most important regions of the Union of Burma from the economic point of view and the soils in the area can be considered as the richest ones of the country ("Rice bowl" of Burma). The density of population is greater than in other parts of the Union.

The material for this description has been borrowed from some of the publications mentioned at the end of this paper, from non-published reports and from information on the spot.

GENERAL

The deltaic area is considered to start at Myanaung 70 km. upstream of Henzada at the limit of the tidal effect. To the west the area borders on the Arakan Yoma mountain range; to the east on the Pegu Yoma range. The city of Rangoon is built on the most southern spur of the Pegu range.

The delta covers an area of about 35,000 sq. km., having a maximum width of about 200 km. and a maximum length of about 290 km. It is a flat and fertile alluvial plain, interwoven with rivers and creeks. Except for a few hills the delta lies below the 15-metre contour.

The region has a population of about 3.5 million and a population density of about 85 per sq. km. (the density for the whole country is 29). Agriculture accounts for the major part of the economic activities.

The geologic history of the area since the beginning of Tertiary times is characterized by the filling in of a large marine gulf covering a major synclinal trough with river-borne sediments from the north and the sides and marine sediments in the south. This gulf occupied the major part of Burma and was bounded on the east by the then newly folded Indo-Malayan mountains and cut off from the Assam Gulf by the incipient ridge of the Arakan Yoma. It is assumed that the great Tertiary river, which may be called the proto-Irrawaddy, flowed into the gulf roughly along the line of the present Chindwin, the major contributary, and later extended southwards, as the gulf became filled in, along the present course of the Lower Irrawaddy. There was probably a parallel river along the line of the Upper Irrawaddy and Sittang, which may be called the proto-Sittang. Thus some major features of the courses of the Chindwin and Lower Irrawaddy were determined prior to the close of the Pliocene.

The history of post-Pliocene times seems to have been marked by a warping which has resulted in the separation of the Upper Irrawaddy and the Sittang.

It is considered that some 300,000 years ago the mouth of the river was still situated near Prome.

The present maximum rate of advance of the deltaic formation is estimated at 5 to 6 km. in 100 years which is equivalent to some 10 sq. km. annually. The whole delta is bordered by mangroves and mud flats in the south where the building of the delta continues at a fast rate. Here the river empties itself into the Andaman Sea through nine large distributaries; from west to east: Bassein, Thetkethaung, Ywe, Pyamalaw, Irrawaddy, Bogale, Pyapon, China Bakir (or To) and Rangoon rivers.

The deltaic area slopes gently from the apex seaward with an average slope of about 5×10^{-5}. Ground elevation at Henzada is about 11.5 metres above mean sea level.

CLIMATE

The rainfall on the drainage basin of the Irrawaddy is governed almost completely by the monsoon winds. Three seasons can be distinguished: (a) the warm and humid rainy season from mid-May to mid-October when the south-westerly monsoons convey a great deal of moisture to Burma across the Bay of Bengal; (b) the cool, dry season when the north-east monsoon is

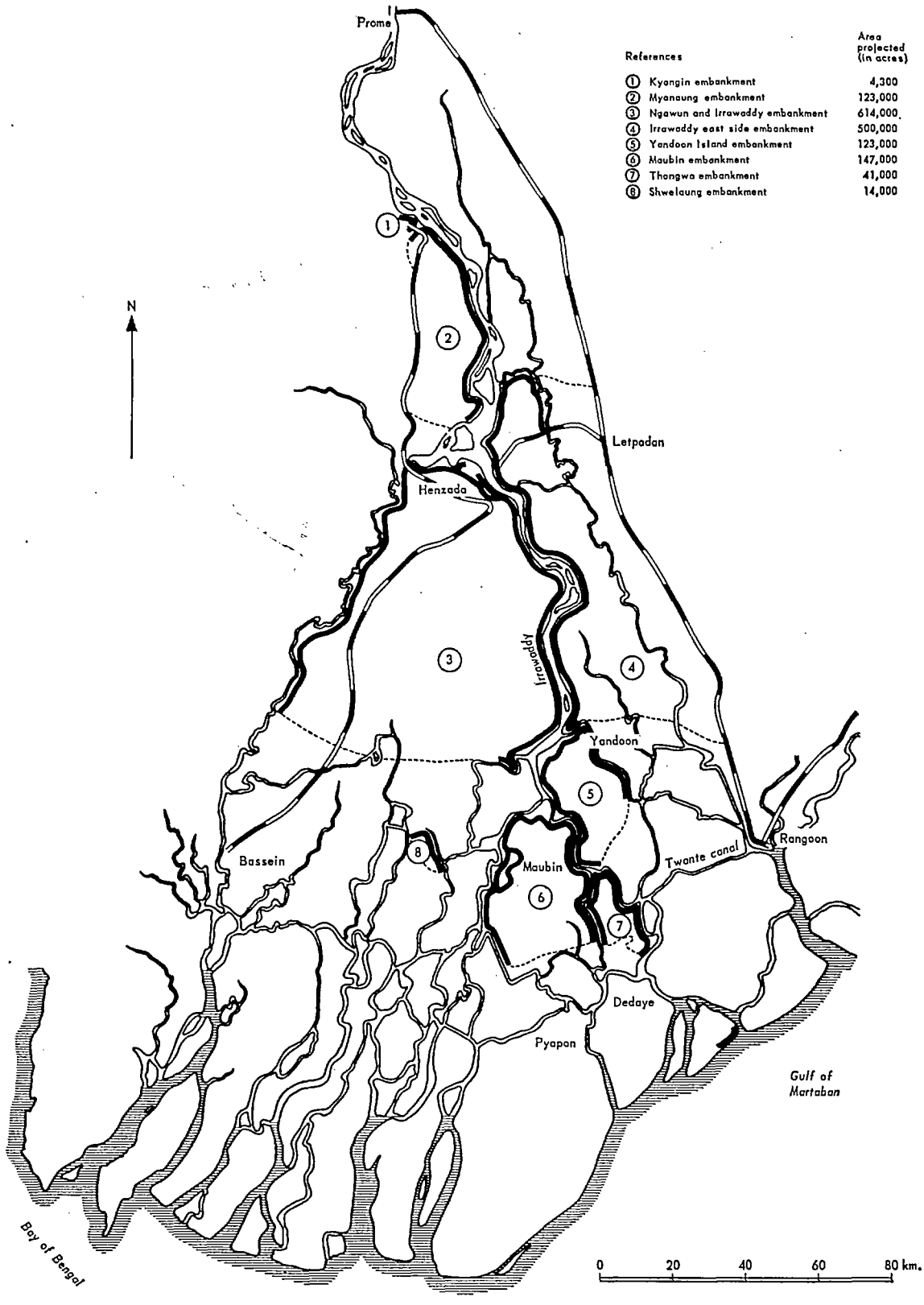

FIG. 1. Deltaic area of Irrawaddy showing protective levees.

dominant from November to February; (c) the hot dry season from March to April.

The average annual rainfall in the upper basin varies between 840 mm. (Mandalay near the dry zone in central Burma) and 3,750 mm. in the extreme north, with an average of 1,750 mm.

TABLE 1. Average temperature and rainfall

Period	Temperature (°C.)	Precipitation (mm.)
January	25.3	1
February	26.4	7
March	28.6	2
April	30.2	102
May	29.1	310
June	27.4	544
July	26.9	591
August	26.9	513
September	27.3	437
October	27.8	200
November	27.2	82
December	25.3	25
Yearly average	27.4	2 812

The rainfall in the delta shows a considerable areal variation. Near the apex the average annual precipitation is 1,500 to 2,000 mm., while in the coastal areas the precipitation varies from 2,500 mm. in the east to 3,500 mm. in the west. This is the highest figure of the deltas in South-East Asia.

The total rainfall does not vary much from year to year and is within some 25 per cent of the normal. The distribution in the course of the year may be irregular.

Over 90 per cent of the rainfall over the delta falls within six months of the year only, i.e., from 15 May to 15 November.

Average figures of rainfall and temperature are given in Table 1.

Thus the temperatures are nearly uniform throughout the year, the seasonal difference in Rangoon being only 4.9° C.

HYDROLOGY

Data on river flow is scarce and the figures on discharges are still based on Gordon's river gauging from 1869 to 1879, at Saiktha, near the apex of the delta. Some data is given below:

Drainage area, 374,000 sq. km.
Highest recorded flood flow (1877), 63,900 cu. metres per sec.
Lowest recorded discharge, 1,306 cu. metres per sec.
Average annual discharge, 13,400 cu. metres per sec.
Annual yield, 423,000 million cu. metres
Annual silt run-off 291 million tons.

Thus the average annual silt content is of the order of 700 mg. per litre which is low compared with some other deltas. In spate the river carries some 1,000 to 1,300 mg. per litre.

Low flow occurs normally in February-March followed by a gentle rise and then a steeper rise in April-May as a result of melting of snow and ice on the mountains in the upper catchment. After a sharp rise in May-June the highest stage is reached in July or August, after which the flood steadily recedes, though late rains in September-October may retard the fall.

The highest recorded flood flow is that of 1877 with a peak discharge of 63,900 cu. metres per sec. The peak stage at that time was 44.3 ft. above mean sea level.

This peak stage has been exceeded time and again since 1877. The highest stage ever recorded is 46.85 ft. in 1947 when the 1939 record of 46.2 ft. was exceeded. Lack of recent gauging makes it difficult to convert the stages into discharges.

When the river level at Henzada is 42.5 ft., with a corresponding discharge of 37,700 cu. metres per sec., it is considered to be dangerously high. The duration of the floods above danger level is approximately 28 days. The flood level is then more or less constant with a variation of 7.5 to 10 cm. for each successive wave of flood.

The flood stages have not been affected by the extension of the delta. This is due to the cutting of loops of the river by which in 60 years a shortening of about 35 km. has taken place.

TIDAL CONDITIONS

Data on the tidal ranges and tidal currents along the coast of the delta are scanty. At Elephant Point at the entrance to the port of Rangoon and close to the sea, the mean spring tidal range is 5.8 metres and the neap tidal range 4.0 metres. In Rangoon, 72 km. from the sea, these ranges are 5.1 and 3.5 metres respectively.

Thus the delta of the Irrawaddy is characterized by the presence of strong tides; the tidal ranges are the highest of all deltaic areas in the humid tropical zone.

Further inland the tides are smaller. At Bassein, 110 km. from the sea, the mean spring tidal range is only 2.2 metres and the mean neap tidal range 1.8 metres. More information on the propagation of the tides into the river distributaries is contained in a figure of an earlier paper on surface hydrology in Section II. Although there are differences in tides between the various points of the long coast (200 km.) no important longshore currents are generated.

An important factor in the delta-building process is the action of the waves generated by the south-west monsoon. The sediments are moving to the east where the strong ebb current of the Rangoon river and, farther away, that of the Sittang river carry the sediments farther offshore. In this way the comparatively low

rate of growth of the delta and the delta front configuration can be explained.

The tidal currents in the estuaries and between the shoals in the coastal waters can be quite strong. In the entrance of the Bassein estuary velocities of 0.75 to 1.5 metres per sec. occur whereas the combined effect of ebb current and river flood discharge may increase velocities up to 3.0 metres per sec.

There occurs hardly any rise of the sea level above the astronomical tides as caused by meteorological effects.

ENGINEERING WORKS

The system of embankments in the deltaic area provides a unique example of partial flood protection. The major dikes existing at present are shown in Figure 1. They form a system of embankments aligned like a horseshoe around the areas between the river distributaries, leaving the downstream ends of the compartments open. In this way, protection of the higher portion of the interdistributary areas is obtained, and the lands can drain freely in a downstream direction. In the event of extreme floods, the lower portions of the compartments act as a flood basin, thus slightly reducing the flood peaks.

At present there are some 1,300 km. of "government embankments" partially protecting some 6,000 sq.km. or about 20 per cent of the total area under paddy in the delta.

This system of open embankments should be considered as a compromise in the controversy between advocates and antagonists of flood protection by diking, a problem which is encountered in many deltaic areas.

The gradual development of embankments will be seen to have followed the increase of population. Until about 1850 much of the delta lands were uncultivated. Following the rush of settlers from Upper to Lower Burma, the construction of embankments to protect fertile areas from being flooded kept pace with the increase of population and the cultivated areas. As early as 1861 a government project was put into operation for the construction of a dike on the west bank of the Irrawaddy.

Many dikes were built around 1880 and 1920 and up to about 1920 diking was considered essential and did not meet much opposition.

The dike system thus constructed, and improved on later, has successfully withstood floods exceeding 57,000 cu. metres per sec.; breaches occurred sometimes with still higher floods or for other reasons.

In 1926 considerable flood damage occurred, mainly to the Burma railways. In the same year the Mississippi disaster occurred; it was attributed to the double embanking of the river. The authorities then began more and more to oppose embankments on both sides of the Irrawaddy and a further extension of the system of "village embankments".

In a report of 1929 of the Public Works Department it was even recommended to demolish the "village embankments" on the east bank at a rate of 16 km. per year, but in view of the costs of compensation or acquisition this suggestion could not be put into practice.

The matter came again to the fore after the big flood of August 1939. On the basis of a comprehensive study it was stated that the best means of flood control would be a distribution of the flood-water over as wide an area as possible. The existing depressions would be filled by the natural process of land-building by a silt-laden river. This would require the ultimate removal of the dikes. Since this would lead to a complete economic ruin of the delta and affect the prosperity of the whole country, it was considered necessary to retain the existing dikes for many years.

Later on no adverse effects were noticed from reaches where double embankments existed and at present the policy of "keeping up the dikes" has been approved by the government. Projects are contemplated to extend the existing dike system still further.

Since no training works of the Irrawaddy have been carried out bank erosion occurs in certain localities. It is not considered economically feasible to train the river and thus losses of land must be accepted. In order to protect the interior land should the dike fail, retired embankments are thrown up at those places where bank erosion is threatening the embankment.

In the coastal zone sea-dikes have been built to protect the lands from being flooded with saline water. Recently the Government carried out some new schemes like the Labutta polder south of Bassein and the Pyapon coastal embankment.

Mention should also be made of the construction of sluices in the embankments for controlled admission of silt-laden river water to raise the land elevation and to improve the natural fertility of the soil. This method is similar to the *colmatage* as applied in Cambodia. A sluice was built in the western embankment of Yandoon Island facing the Irrawaddy near Mithwechaung. It effectively promoted silting up of the vicinity of the inlet but the difficulty is to get the sediments farther away in the proper depression.

FLOOD CONDITIONS

In the area where the river stages solely depend on the upstream floods, embankments have proved to be successful in checking the floods. There is, however, still damage to the crops because of inadequate facilities to drain off local rainfall.

As far as the reach of the Irrawaddy between Henzada and Yandoon is concerned (see Fig. 1), the dikes on the left bank (eastern side) of the river are lower than the ones on the right bank so that in case of extreme floods the area to the east will be flooded first, relieving the other area. The inevitable consequence of this system of flood-plain zoning is that thea gricultural conditions

in the former area are still poorer than in the better protected zone.

The open downstream ends of the embankments are located in the intermediate zone. As explained in the paper on surface hydrology in Section II both the tides and the river floods affect the river stages in this zone but the rise caused by the river flood is only one-fifth or so of that at the upstream end of the embankments.

The flood levels and the tides penetrate through the open ends of the compartments flooding the lowest downstream land areas, but the propagation of the tides is hampered by the hydraulic resistance of the land flooded to a small depth and over a long distance. Thus it was found that in Maubin Island, where at the end of the embankments the high flood level can be 3 metres above mean sea level, cultivation of paddy can still be carried out on land about 1.5 metres above mean sea level high, i.e., about 1.5 metres below the high flood level.

There still remain large tracts of land that are deeply flooded and not under cultivation. There is stagnant water even during the dry period.

Conditions are still more unfavourable in Yandoon Island which is smaller and where the downstream flood levels can penetrate both from the south and from the east. The major portion of this island is almost permanently submerged and cultivation is limited to a rather narrow fringe on and near the natural levee.

The situation would be improved by closing the open embankments at the downstream ends. Since in this way the natural drainage from upstream would be hampered, an extensive system of drainage canals and collectors in the compartments, as well as outfalls with sluices, would be required. For drainage of the whole area of Yandoon and other islands pumping would be necessary since many tens of thousands of hectares in Yandoon Island are situated below the + 1.0 metre mean sea level contour, i.e., at low tide level in the flood season.

As can be seen from Figure 1 there are large areas farther downstream but still in the intermediate zone which are not protected at all. To a certain extent these areas can be cultivated, since the depth of flooding is moderate and the river water during the rainy season is fresh. The flooding can be partly checked by the field dikes. Low-lying patches in the back swamps are not cultivated.

In the coastal zone about 5,200 sq. km. are below high spring tide level and are subject to flooding with more or less saline water. This is likely to occur in September-October when the river floods recede and south-westerly winds cause some piling up of the sea above the level of the high spring tides. A large part of the coastal zone consists of mangrove forests and in other parts cultivation is limited to higher patches. Sandy ridges, such as old beaches and sandbanks, provide a natural refuge.

As mentioned earlier a modest start has been made with the construction of sea-dikes to halt the salt-water flooding.

AGRICULTURE AND LIVING CONDITIONS

In the delta single rice cropping during the wet monsoon is still predominant. Two-thirds of the total cultivated area is given to rice. Multiple cropping is difficult because of the shortage of water during the dry season and the absence of irrigation facilities. The total productivity is about 40 per cent of the national total.

Winter rice, having a long growing period, is commonly grown in the delta and spring rice only on a very limited acreage.

Various varieties, adapted to the local hydrologic conditions, are used. Despite the very primitive method of culture, the transplanting method is generally adopted. After transplanting, weeding is done once or twice before the harvest or not at all. Application of fertilizers is negligible.

The yield in the delta amounts to some 2,000-2,500 kg. per hectare and is higher than the country's average (1,700 kg. per hectare). Complete failures seldom occur and there is always the possibility of replanting in July and August. If there is a second failure groundnuts can be tried.

The prevailing size of the holdings in the delta is 4 to 5 hectares against 2 to 4 hectares for the country as a whole. In the vicinity of the cities, where other activities have a share, the holdings are smaller (3.5 hectares) and productivity is also slightly lower [1].

Whereas the total production in the delta is still below the pre-war level, the yield per hectare is increasing. The decrease of production is due to the reduction of cultivated area by the shortage of labour. Cultivation is concentrated in areas with better soils and areas with poor soils have been abandoned. Hence the increase of yield.

Only a part of the lands in the delta is being cultivated. Of a gross area of 3.7 million acres situated in the Bassein, Myaungmya, Henzada, Pyapon and Maubin districts, 1,063,000 acres are subject to inundation to such an extent that cultivation is not possible.

TABLE 2. Decrease in arable land

District	Cultivated land area (acres)		Badly drained land (acres)
	Pre-war	Post-war	
Bassein	987 690	626 935	26 678
Myaungmya	977 190	651 413	15 794
Pyapon	755 174	480 000	120 850

1. Results of an inquiry into 628 holdings in the vicinity of cities.

The decrease in arable land area after the war, taking three districts as examples, is shown in Table 2.

The pattern of human settlement is characteristic of many deltaic areas. It is governed by the geomorphologic features and the flood protection system. Thus the natural levees along the creeks and the rivers and the embankments are preferred perimeters leading to a linear settlement. The need for an adequate supply of water toward the end of the dry season accentuates the trend to creek-side building. Throughout the delta, moreover, communication is easiest by water and fishing is a subsidiary occupation; in the smaller villages practically every householder has his own boat.

The linear type of settlement is found also on old beach lines in the delta. Here and there in the mangrove swamps and tidal forests are low sandy ridges—old beaches and sandbanks. The soil is often sandy or loamy and their elevation is enough to bring them above all but exceptional floods. Fresh ground water is found in the sand floating on the denser saline ground water.

The larger villages may have several hundred houses and populations of 2,000 to 3,000. Nucleated villages which are not uncommon on slight rises are generally smaller.

Some 95 per cent of the houses consist of single storeys with verandas, built on piles to raise them 0.5 to 1.5 metres or more from the ground. The framework is of timber posts, the walls of woven bamboo. Roofs are generally thatched and in the larger villages corrugated iron is popular.

TRANSPORT AND COMMUNICATIONS

The rivers and creeks of the delta remain the only and convenient means of transport for a large volume of rice and consumer goods and passenger travel. The Irrawaddy itself is a very important artery of trade for a large part of Burma and commercial transportation can be maintained throughout the whole year from Rangoon to Bhamo, a distance of 1,350 km.

In the Irrawaddy delta downstream of Henzada there are more than 3,000 km. of commercially navigable waterways and thousands of kilometres of other streams used by sampans and country boats.

Most waterways are natural watercourses. There is no system of dredged canals as exists in the delta of the Mekong river. The two exceptions are the Twante canal (35 km.) (see Fig. 1), shortening the connexion between Rangoon and the western part of the delta, and the Pegu-Sittang, which, however, is outside the Irrawaddy delta proper.

The craft operating in the delta may be distinguished as government craft, craft operated by private or contract carriers, sampans and country boats and rafts of bamboo and timber. The government craft are operated by the well-organized Inland Water Transport Board, which took over the operations of the Irrawaddy Flotilla Company in 1948.

The largest steamers of the Irrawaddy fleet are the express mail steamers plying between Rangoon and Mandalay and between Rangoon and Bassein in the delta. In most cases the vessels moor alongside the river bank. In the upper part of the delta there are usually two landing stages, one used during the high water period, the other during the dry season. Cargo storage facilities are available in Rangoon and Bassein, but in many other localities the goods are stored either on barges, some of which are roofed, or openly on the river banks.

The land areas in the deltas, with their innumerable creeks and vast areas of waterlogged land, are not practicable for either roads or railways, except along the few stretches of high-lying ground and along the embankments. There exist some secondary roads especially in the northern part, e.g., between Henzada and Danubyu and near Maubin and Pyapon. Bassein can be reached by railway from Rangoon by a detour (Rangoon to Letpadan to Tharrawaw (by ferryboat) to Henzada to Bassein) (see Fig. 1).

Where the farm houses are built along rivers and creeks the farmers reach their land by walking on the field dikes or directly over the field when this is possible. A part of the farmers' products is brought to the markets or towns in large sampans or barges drawn by tugs.

Résumé

La région deltaïque du fleuve Iraouaddi en Birmanie (A. Volker)

La région deltaïque de l'Iraouaddi, en Birmanie, présente un exemple caractéristique de deltas dans une région tropicale humide au début de l'aménagement hydraulique et agricole. C'est l'une des plus importantes régions de l'Union birmane du point de vue économique, et les sols de cette région peuvent être considérés comme les plus riches du pays (le « bol à riz » de la Birmanie). La population est plus dense que dans aucune autre région de l'Union.

L'auteur traite successivement les questions suivantes : histoire, géologique, climat, hydrologie, marais, grands travaux, inondations, agriculture et conditions de vie, transports et communications.

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General features of the delta of the Amazon

H. Sioli

When speaking of the delta of the Amazon we refer to the estuary of the mightiest river in the world (Fig. 1), not the mightiest in length but in volume of water. It has been estimated by Katzer (1903) that the Amazon pours into the Atlantic about 120,000 cu. metres of water per second in the dry season; a figure which is exceeded in the high-water season [1].

This tremendous mass of water corresponds to the size of the estuary of the river: where the mouth opens into the ocean, it is nearly 340 km. wide, between the Cabo do Norte in the north-west and the Ponta da Tijuca in the south-east. The point at which the lower course of the Amazon ends and its estuary begins is generally considered to be the mouth of the Xingú river. Thus the region is about 380 km. long, covering a triangular area of 85,500 sq. km. from river shore to river shore, not including the alluvial lands on both sides. When these and other lands, built up or influenced by the Amazon on the shore strips of its mouth region, are added, the whole estuary zone comprises 100,000 sq. km. or more.

Great parts of that region, but not all of it, consist of alluvial lands, deposited by the Amazon in geologically recent times. But in spite of the intensive sedimentation activity of the river with its turbid water, the mouth zone of the Amazon does not represent a true delta. In fact, the wide, more or less triangular shaped *golfão* (great gulf), as the Brazilians call it, contains innumerable islands, the largest of them being the island of Marajó (which alone occupies 47,964 sq. km.), followed by the islands of Caviana (4,968 sq. km.) and Mexiana (1,534 sq. km.), which are nearest to the sea, and the Ilha Grande de Gurupá (4,864 sq. km.), the uppermost one at the beginning of the estuary, coming down river. But nowhere have we an advancing growth of islands into the ocean; on the contrary, the north-eastern coast of Marajó is being eroded by the action of the sea.

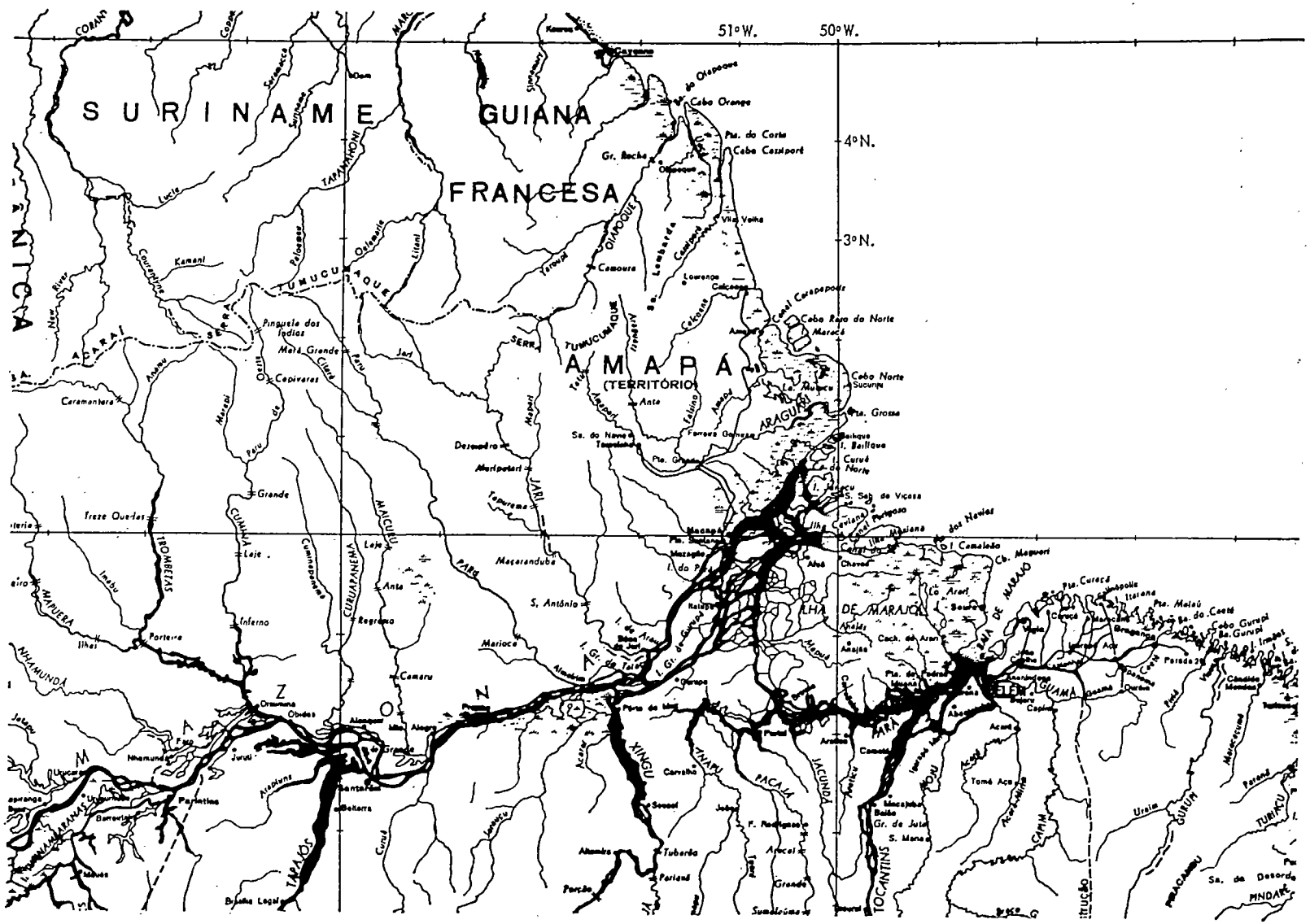
The absence of a true delta development which would advance into the sea is surprising since the lower Amazon carries turbid muddy water with a suspension load of $\pm$ 50 to $\pm$ 200 p.p.m. in the low-water and flood seasons respectively (Sioli, 1951, 1957), with a total annual transport of suspended solids into the ocean to the order of 1,000 million tons (estimated by Katzer, 1903).

Absence of a real delta is easily explained by the existence of an ocean current along the Brazilian coast (Equatorial Current). The Amazon water, rich in sediments, instead of spreading straight out over a great area after its outflow from the river channel into the open ocean and its current being subsequently slowed down—factors which would cause the formation of a real delta with a fan of elongated islands—is interfered with by the ocean current coming from the south-east up the Brazilian coast and deflected along the Guiana coast. It is there where the expected sedimentation occurs: along the Atlantic shore of the Território Federal do Amapá, in Brazil, and farther north in French Guiana, the coastal zone consists of young deposits of Amazonian fresh water sediments extending over 80 km., which corresponds perfectly to the alluvial flood lands of the lower Amazon, the so-called *várzea*, and represents a prolongation of the latter.

These Amazonian flood lands along the Atlantic shore should therefore, because of their origin, be included in what is considered to be the estuary of the Amazon.

During the dry season, called "summer" in Amazonia, this zone is only partially dry and almost everywhere muddy; during the rainy season, the Amazonian "winter", it is flooded by 4 metres of water. It is mainly covered with grasslands (*campo inundavel*), and, in parts, with forest subject to flooding. In the many lakes, which are always shallow with open water, there may occur the curious phenomenon of floating

1. The most recent determinations made by the United States Geological Survey during the high-water and low-water seasons of 1963 showed an average annual discharge of 226,000 cu. metres per sec.


SURINAME
GUIANA
FRANCESA
AMAPÁ
(TERRITÓRIO)
ILHA DE MARAJÓ
51° W.
50° W.
4° N.
3° N.
Cabo Orange
Pta. do Corte
Cabo Cassiporé
Vila Velha
Cabo Raso do Norte
Cabo Norte
Pta. Grossa
Ilha Bailique
Macapá
Santana
Belém
Ilha Mosqueiro
Ilha Caviana
Ilha Marajó
Ilha Tocantins
Ilha Guajará
Ilha Grande
Ilha Arapiranga
Ilha Tatuoca
Ilha Jutaí
Ilha Arauaí
Ilha Tapiranga
Ilha Paquetá
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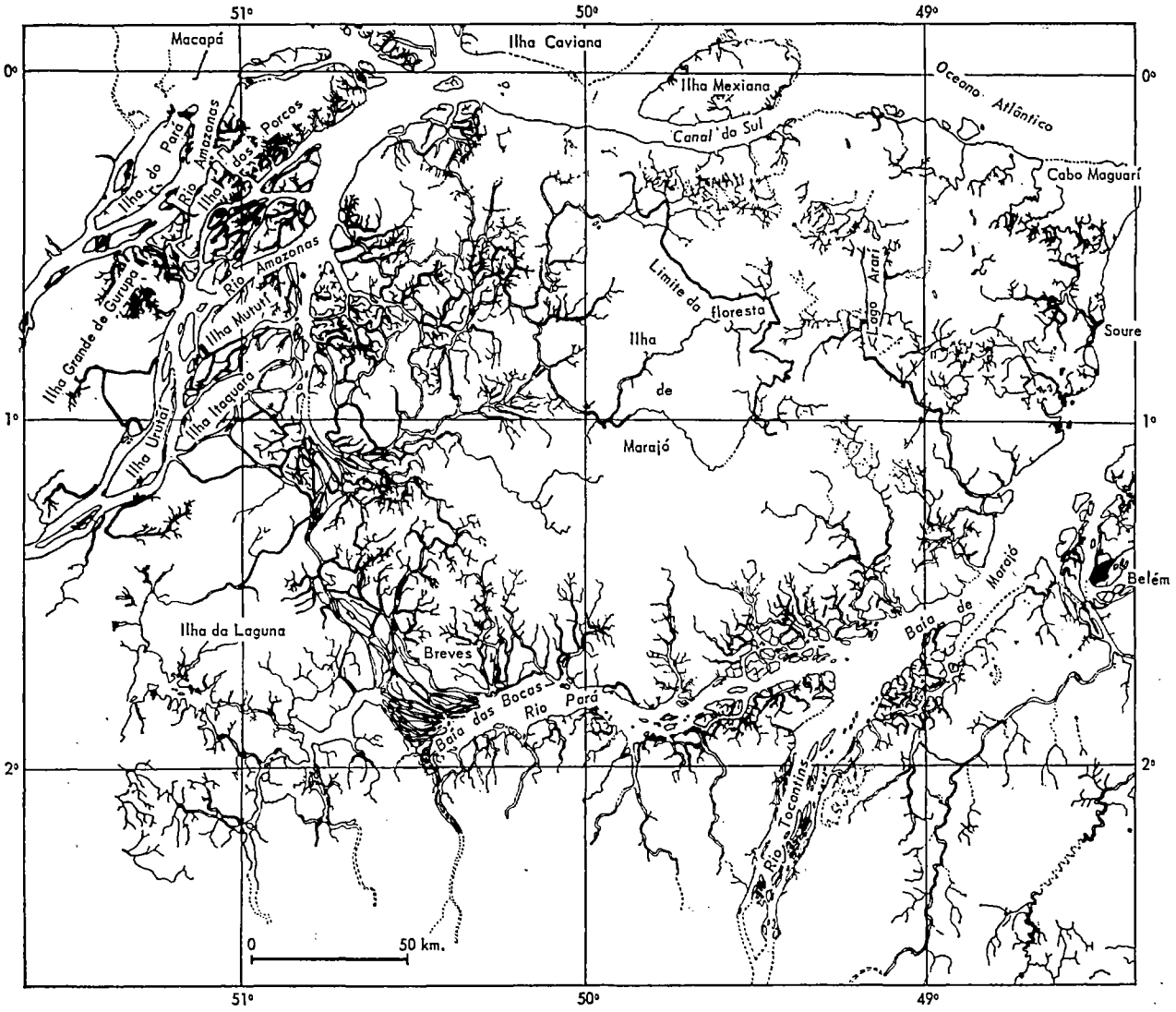

FIG. 2. Map of the Estreitos de Breves (Região dos Furos), west of Marajó Island. (After Preliminary Map of Amazon Delta, 1 : 500,000, compiled by the United States Geological Survey, 1943, sheet 2.)

islands, even with high trees standing on them, which may be drifted across the lake by the wind.

In an inland direction the alluvial zone subject to flooding finally ends and gives way to higher terrain, the *terra firme*, which consists of Tertiary (Pliocene-Pleistocene) fresh water sediments of clays and sands, i.e., the layers of the *Série das Barreiras* or of archean granites.

We have seen that the mouth of the Amazon is no real delta, but that it is more similar to a large and wide estuary, the opening of which is divided into two parts by the vast island of Marajó. North of it there is the main outlet of the Amazon, the northern channel, through which passes the greater part of the water mass. The southern part of the double estuary is called Rio Pará; it receives only a very small proportion of Amazon water through the channels of the Estreitos de Breves, while it serves more as the outlet of the Rio Tocantins and the other smaller rivers which flow into the western, dead-end part of the Rio Pará with its several wide *baías*. Whether the Rio Tocantins is or was once an affluent of the Amazon is still a controversial question. But since there are no fundamental differences between the main mouth of the Amazon, north of Marajó, and the zone of the Rio Pará, that question is more an academic one which does not affect the physiognomic unity of the entire double estuary.

As opposed to the majority of the other numerous islands in the Amazonian *golfão* the islands of Marajó, Caviana and Mexiana are not totally of alluvial origin. They partly consist of consolidated *terra firme*, terrains of early Quarternary age (Pleistocene) which have been

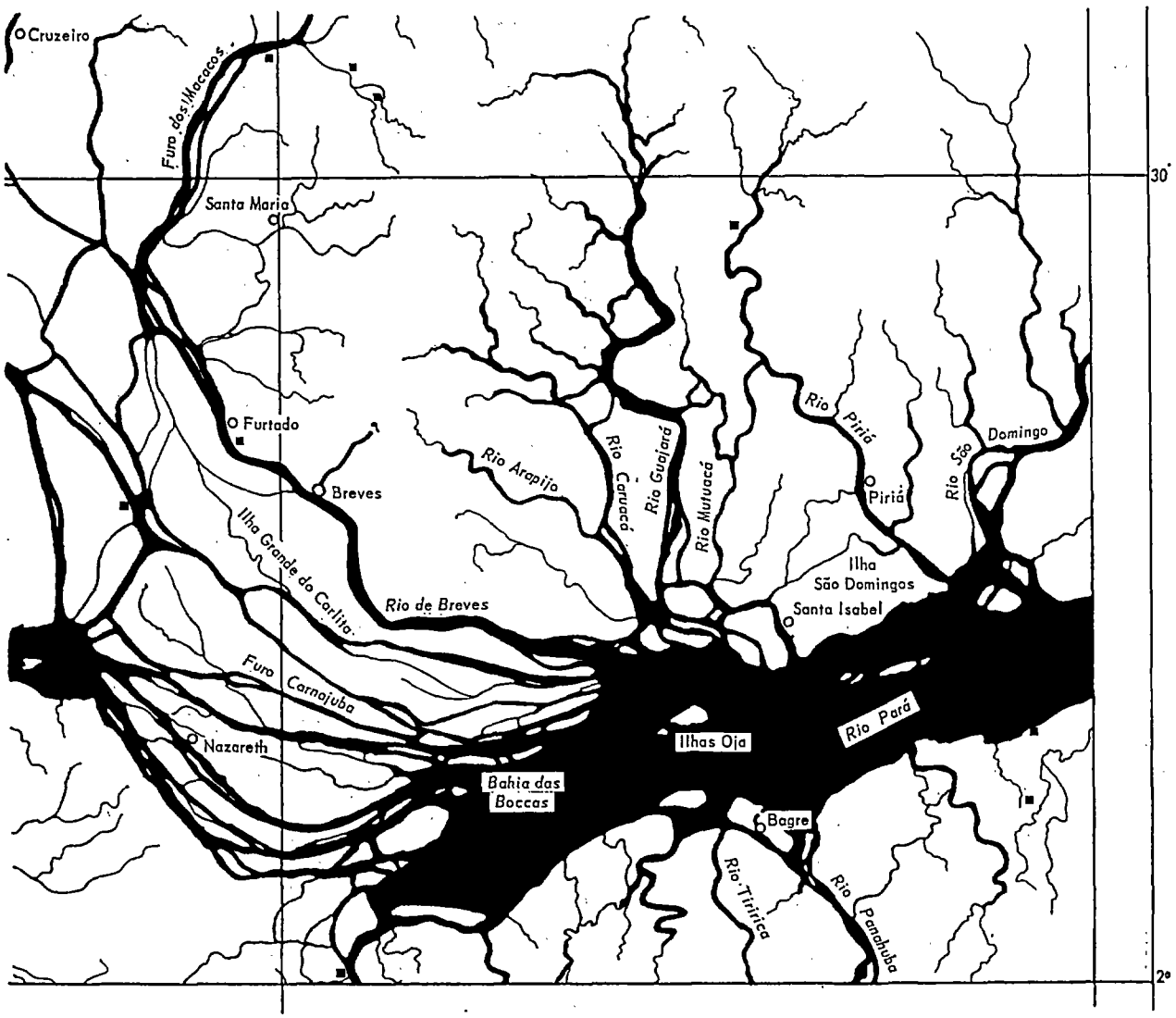

FIG. 3. Map of the internal delta of the Amazon at the outlet of the Estreitos de Breves into the Rio Pará. (Partial Reproduction of the Mazagão map (946 A), 1: 500,000, AAF preliminary base, 1948. Reproduced from IBGE, Geografia do Brasil, Grande Região Norte, *Bibl. Geogr. Bras.*, Vol. 1, 1959.)

separated from the continent by tectonic movements. That is the case in the whole eastern part of Marajó, while the western part of that island is built up by alluvials.

The above-mentioned islands of Mexiana and Caviana with others (Jurupari, Janaucú, Bailique) form a group which occupies almost the whole estuary of the northern mouth of the Amazon, leaving open a wide and more or less deep channel directly along the north bank of the river bed through which the greatest part of the water of the Amazon flows into the sea. These islands are subject to the influence of the ocean; the watercourses of their creeks are daily invaded by the tides, the eastern coastal strips are covered with mangrove, and around the island there is brackish water. The same characteristics predominate also on the northern and eastern coast of Marajó, where instead of sedimentation—as would be the most typical feature for a real delta formation—there even occurs the already-mentioned erosion by the action of the sea.

Farther up the Amazon from this island group is another which is already typically fluvial. These islands —to name only the larger ones : Ilha Grande de Gurupá, Ilha dos Porcos, do Pará, Mututí, Uituquara—are surrounded by Amazonian fresh water. Their vegetation is no longer of the littoral type or, still less, mangrove but the same as on the lower Amazonian *várzea*. They are probably all of alluvial origin showing that inside the estuarine mouth of the Amazon there

PLATE X.
Reproduction of the map, made by Huber, 1903, of the water currents in the Estreitos de Breves. The black lines represent the shorelines of the Amazon and of the estuary of the Pará; the dotted lines represent the limits between the districts of the Região dos Furos (Estreitos de Breves); the arrows indicate the direction of the currents during ebb-tide.

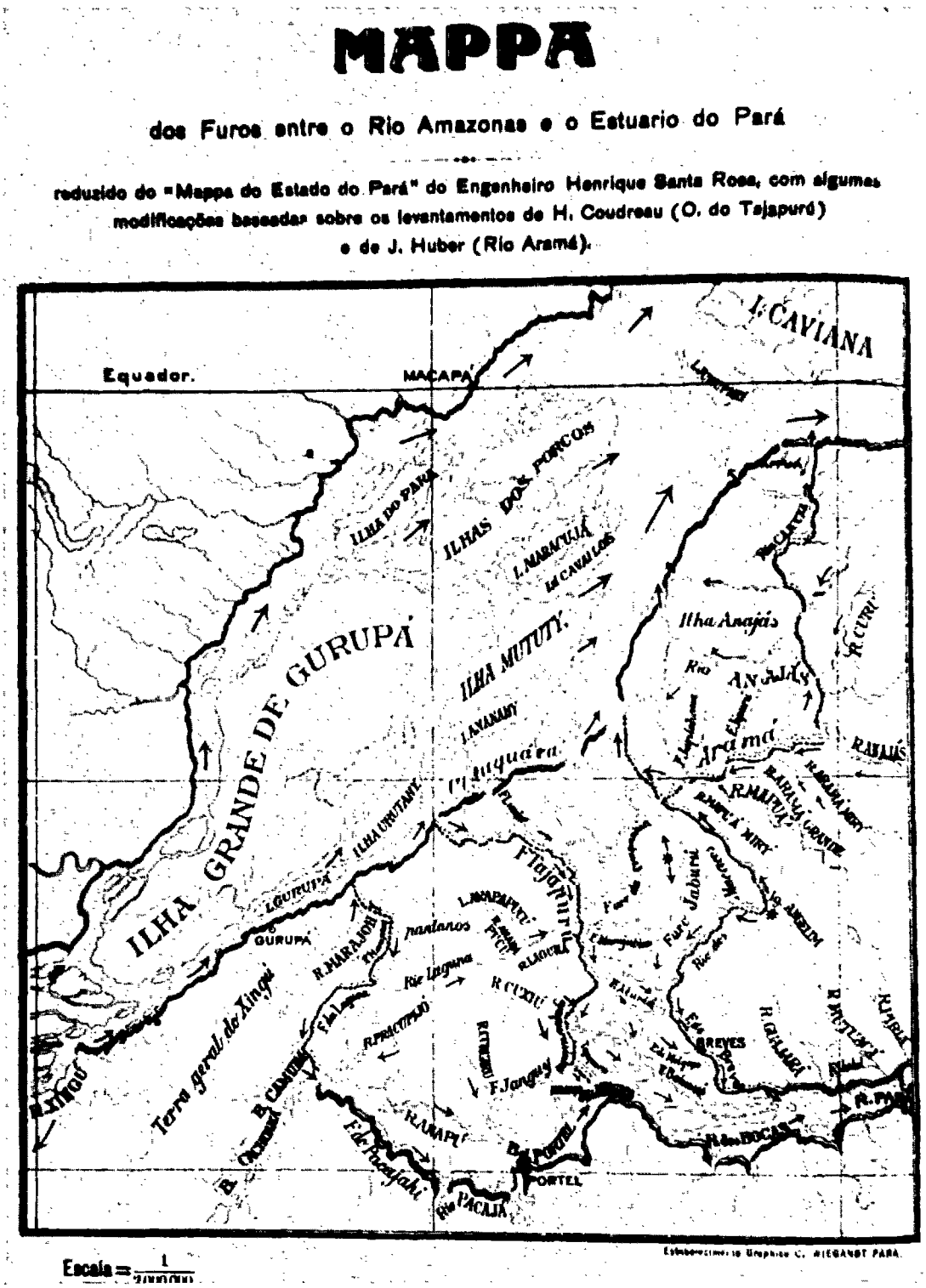

PLATE XI.
Estuarine alluvial forest on islands of the Estreitos de Breves.

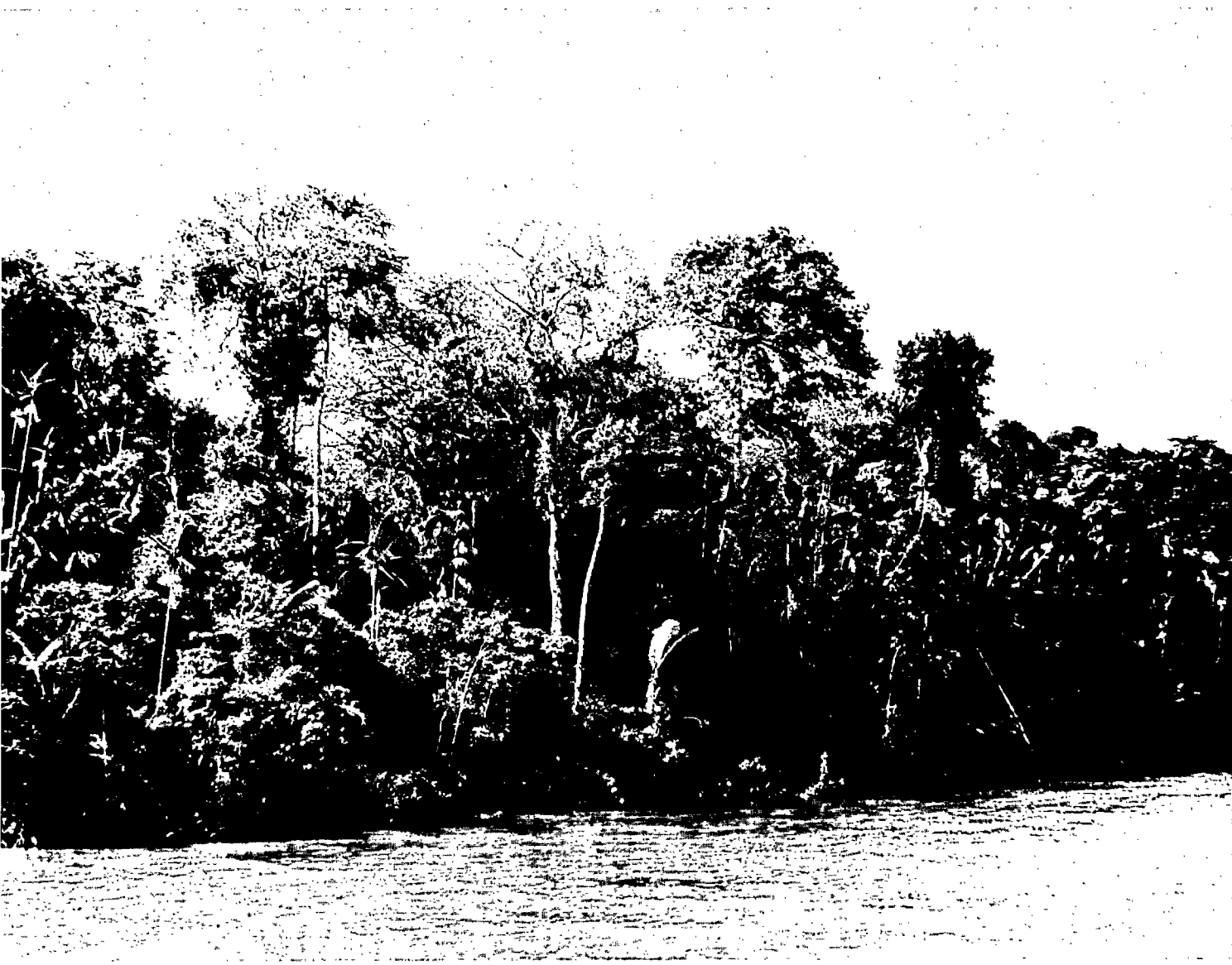

PLATE XII.
Campo, not subject to flooding, on the right side of the Rio Pará, between Belém and Vigia, with a flora corresponding to the *cerrado* of Central Brazil.

PLATE XIII *(overleaf)*. A remnant of high forest on *terra firme* in the Bragança region, east of Belém.

prevail conditions which under other circumstances in the ocean at the river mouth (absence of the current along the coast) would lead to the formation of a protruding delta.

But there is a section in the Amazonian estuary where we can observe not only intensive sedimentation and formation of islands but the evolution of a true delta, if only an internal one and on a relatively small scale. We refer here to the very interesting zone southwest of Marajó, between that island and the continent where the Amazon communicates with the Rio Pará through a labyrinth system of long and narrow channels, known locally as *furos*, and alluvial islands. The region is called Estreitos de Breves (Fig. 2).

In the *furos* the water flows alternately in opposite directions owing to the influence of the tides which raise and lower the water level twice a day (Plate X). It is not salt or brackish water which enters these channels, but fresh water which is forced back into them by the tidal wave, coming up the Amazon from one side and the Rio Pará from the other side, which flows out again after the tide turns. Therefore there are certain points in the *furos* where the currents, coming from opposite sides, meet and where they separate again when turning. These points with no horizontal currents and only the rising and falling movements of the water level are called *repartimento* by the local inhabitants and are well observed because of their value in estimating the time and work needed for travel in paddle-driven dug-outs. In spite of the forward and backward movements of the water mass in the Estreitos de Breves, some water from the Amazon itself passes through them into the Rio Pará, and it is this muddy Amazon water which has built up all the islands between Marajó and the continent. Here is the true delta of the mouth of the Amazon (Fig. 3), admittedly only an internal one, but it is more impressive when we enter the waterways of the narrow, deep channels and see the flat, low, luxuriant, jungle-covered islands, the surfaces of which are at the level of high tides and just flooded by them. The map shows that the islands have grown in the form of fingers or of a fan into the water of the Baía das Bocas of the Rio Pará, except that the fan is not opened, but a bit compressed by the relative narrowness of that *baía*. In spite of this peculiarity no more typical form of a delta can be imagined.

The question arises how these islands, and between them the channels which are from 6 to 40 metres deep and 50 to 450 metres wide, might have originated.

That the channels are the result of erosion in a terrain that always had the same height is refuted by the fact that the majority of the islands consist of very young alluvial sediments, the deposition of which still continues.

A slow sedimentation on a base which originally had been lying deeply under the water level is also not conceivable. The result would have been islands of great areas between wide, flat channels such as we find in the mouth of the Amazon north of Marajó.

The situation, however, becomes different when we assume that a terrain which had originally been more or less at water level slowly became more and more submerged below the water surface either by the post-glacial rise of the ocean level, or by subsidence of the land, or by both processes acting simultaneously or one after the other. During such a slow change of the water level in relation to the elevation of the land surface, the muddy Amazon water, flowing over that shallow area, will have had time to deposit banks of sediments and to form between them tidal channels. Then it was possible that, with a continuing slow rise of the water level, the sediment banks would thicken with each high tide through the addition of a new thin sediment layer, while the creeks maintained their channels always open and at their original depths, i.e., always deeper than the water surface. In this way the creeks in the recently deposited alluvial zone south west of Marajó transformed themselves into the *furos*, the deep channels with more or less steep bed walls of today; the results of such processes must finally lead to a situation we actually find in the Estreitos de Breves with their labyrinth of channels and islands.

The flooding of the estuary of the Amazon in more or less recent, post-glacial times corresponds to the explanation of the topography of the lower sections of almost all lower Amazon affluents. Practically all these, if they are "clear-water" rivers, between the Rio Tefé on the Middle Solimões and the Rio Xingú, have unproportionally wide and, in many cases, also deep lake-like lower sections which are separated from the upper courses by a zone of elongated alluvial islands ("sedimentation zone") which are still growing downstream through continuing deposition. These lower river-courses were considered to be fresh-water *rias*, that is drowned valleys, i.e., valleys which developed widely and deeply in the soft tertiary sediments of that region during the period of low ocean level causing strong river currents on account of their steepened gradient. Mainly because of the post-glacial rise of the ocean level, which had its effect on that flat country over more than 2,500 km. up the river, they then became drowned.

The thalweg of the lower Amazon itself has also the same geohistorical background with the only difference that, on account of the great sediment load of the Amazon water, the "sedimentation zone" has already reached the mouth, filling the whole lower course, and even going beyond it so that it continues now along the Guiana coast instead of occupying only the upper part of the drowned valley, which is what happened with the clear-water affluents.

Hence we can see the peculiar feature of the estuary of the Amazon as a result of the young geological history of the topography of the whole lower Amazon system: when, during the glacial periods, the ocean level was still 100 metres or more lower than now,

the river had a much steeper gradient and consequently a much faster current. The strong current carved a large, wide channel into the soft terrain, spreading out with an estuary into the sea.

Inside that estuary the *terra firme* part of the island of Marajó, however, has not been eroded. It might have always divided the mouth of the Amazon into two arms, but we cannot decide whether, during the time of lower sea level, the area south-west of Marajó had ever been flooded, or if it was temporarily dry land, separating the real mouth of the Amazon in the north completely from the common estuary of the rivers east of the Xingú. It is quite possible that at that time there was no aquatic connexion between the two river mouths.

It also seems necessary to suppose that not only eustatic variation of the ocean level but also the vertical movements of the earth's crust played a part in bringing the Amazonian estuary to its present shape. Without such movements it would be hard to believe that just north-west and west of the deep flat land between the Xingú and Marajó we have the highest section of all Amazonia with the sedimental layers of the bottom of the Pliocene-Pleistocene Amazonian fresh-water lake actually elevated up to more than 300 metres. Moreover, the uplifting of that area cannot be old; it must be relatively recent, since we miss in it the wide drowned lower courses of the affluents; a fact all the more remarkable that this peculiar topography shows in all the affluents of the Amazon farther upstream, beginning with the Rio Tapajós, and farther downstream, at Rio Xingú, Baía Pracaí and Caxiuaná.

Perhaps we are to conclude that the block situated more or less between the Rio Tapajós and the Rio Xingú on the southern side of the Amazon, and between the Rio Trombetas-Erepecurú and the Rio Jarí on the northern side, has been uplifted during the late Pleistocene or after the glacial period, while east of that region the terrain strongly subsided south-west of Marajó, but less or not at all at the most eastern part of that island.

These hypothetical movements, however, could not have happened in direct or immediate connexion with the formation of the Marajó-Graben and the other Horsts and Grabens which have been discovered under the lower Amazon by the geophysical studies and drillings made for "Petrobrás", the Brazilian petroleum company.

In the region around Belém we also find direct proof of an alteration in the relation between sea level and land level. Not only on the bottom of the Baía de Marajó, near the Ilha Cotijúba, are there banks of canga-stone (ground water laterite), covered by the water during high tide and barely uncovered at low tide, but also in the lowest part of the city of Belém, under the constantly wet and swampy alluvial land, there has been found, on the occasion of underground studies for buildings, a layer of cangastone in an actual depth of 16 metres. This ground water laterite forms only in the contact zone of ground water with air in the soil, hence we must conclude that the ground water level was once 16 metres deeper than it is now.

As a result of that relatively recent geological event we have not only the estuary of the Amazon shaped as it is now, but we also find two types of soils. In the eastern half of Marajó, on some parts of the Caviana and Mexiana islands, and on stretches along the shores of the estuary, i.e., where there is *terra firme*, the soils developed from the clayey-loamy to sandy sediments of the Pliocene-Pleistocene Amazonian fresh water lake which extended from the foot of the Andes to the Atlantic. In the geological maps of the Amazon the *terra firme* in and around the estuary of the Amazon is distinguished from the other Pliocene-Pleistocene deposits in lower Amazonia (called Série das Barreiras) by the name Formacão Pará as being younger and only Quaternary-Pleistocene, while the Série das Barreiras is said to be of Pliocene (Tertiary) - Pleistocene age. Hence the Formacão Pará is represented by the same colour as the recent fluvial alluvions. But there is no proof of a temporally different origin of the Formacão Pará and the Série das Barreiras. In physical and chemical aspects they are identical as are the soils which formed on them.

The recent alluvial lands, however, are completely different. By far the greatest part of the accumulated material has been brought by the Amazon and its white-water affluents, after multiple intermediate deposition and renewed erosion and transportation, from the slopes of the Andes where the weathering crust of a mineralogically manifold subsoil is constantly washed down into the river and the Amazonian lowlands. The material of the alluvial lands in the Amazonian estuary is more neutral and richer in mineral nutrient reserves for plant growth than is the Pliocene-Pleistocene *terra firme*.

The special edaphic conditions of the Amazonian estuary, however, will be treated under another topic of this symposium.

The climate of the Amazonian estuary is uniform in all parts of that zone only with regard to temperature and humidity of the air. The average temperature is about 27° C. during the whole year with a variation of less than 2° C, between dry and rainy seasons. The average maxima and minima are about 32° C. and 23° C. respectively. The average relative humidity of the air in the entire estuary is above 85 per cent.

Not so uniform is the climate of the zone with regard to the quantity and still more to the distribution of the rainfall during the course of the year. The whole estuary is under the influence of the trade winds blowing from north-east or south-east corresponding to the summer or the winter of the Southern Hemisphere respectively. These winds bring a higher rainfall of $\pm$ 2,900 mm. at Soure, on the eastern coast of Marajó,

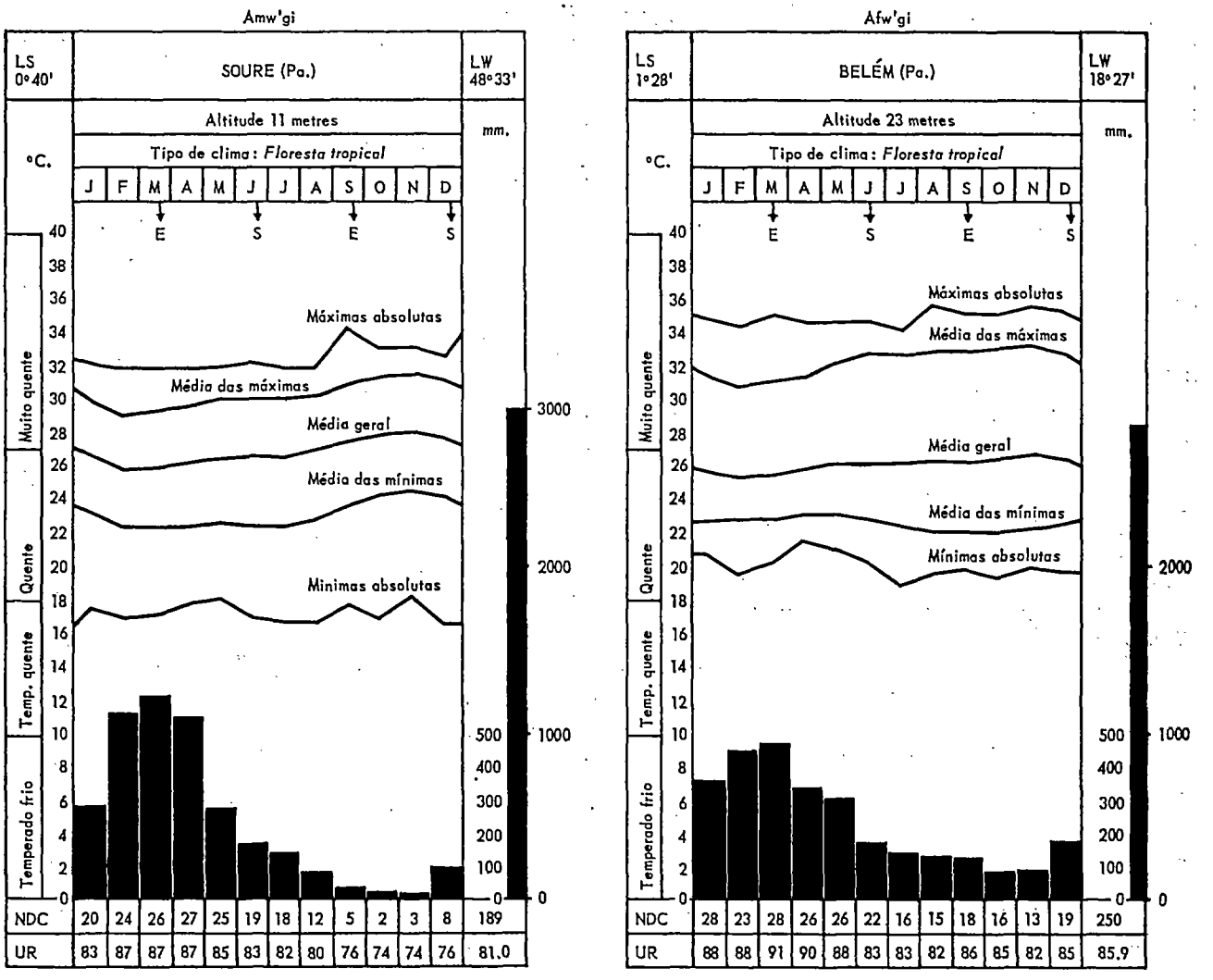

FIG. 4. Distribution of the rains at Soure and at Belém. (Reproduced from IBGE, Geografia do Brasil, Grande Região Norte, *Bibl. Geogr. Bras.*, Vol. 1, 1959.)

and of ± 2,800 mm. at Belém, but of only 2,000 mm. at Macapá and Arumanduba.

The types of distribution of the rains over the year are best shown by means of two typical graphs, from Soure and from Belém (Fig. 4). They show that different distribution does not coincide with different annual amounts of rainfall. In both cases the main precipitation takes place in the first half of the year, but the difference between the rainy and dry seasons is much more significant in the first case (that of Soure) which in this respect is representative of almost the entire estuary. The climate belongs to the Am-type of Köppen's classification. At Soure, with 189 rain days per year, only 10 days are rainy in the three "summer" months September, October, and November with 67.7 mm. of rain against 2,849.6 mm. in the other nine months of the year (16.1 mm. in November against 627.2 mm. in March, as minimum and maximum of the year).

A different type, however, is the second case, the climate of Belém, which is considered as one of the Koppen's type Af because of the more equal distribution of the rain over the year : of 250 rain days during the whole year, 47 are in the driest months of September, October and November, and 296.3 mm. of rain fall in the same "summer" months against 2,435.7 mm. in the remaining nine months (86.0 mm. in November against 435.9 mm. in March).

This climatic peculiarity of Belém is only local and prevails only in a restricted area.

Macapá, on the north-western side of the Amazon estuary, has a climatic type which is an exception in the opposite direction. It seems to correspond more to Koppen's type Aw, since the dry season is still more pronounced than is generally the case. Even in the

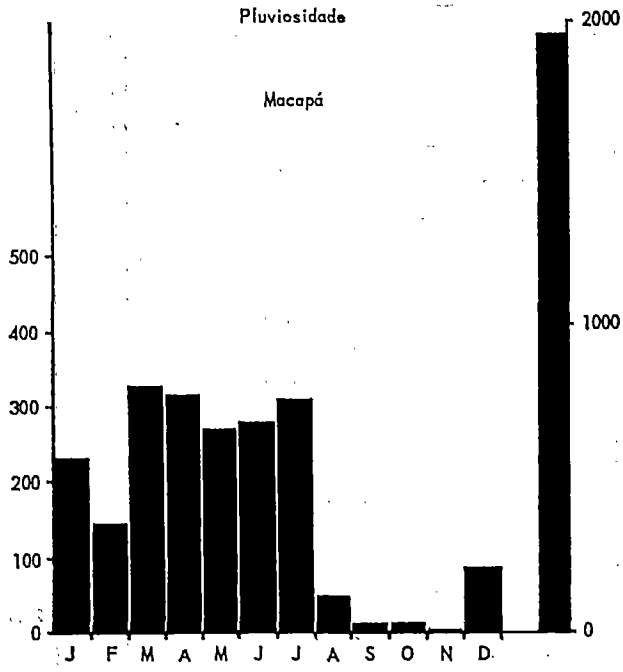

FIG. 5. Distribution of rainfall at Macapá. (Reproduced from IBGE, Geografia do Brasil, Grande Região Norte, *Bibl. Geogr. Bras.*, Vol. 1. 1959.)

driest month, which is November, 0 mm. is shown (Fig. 5).

With regard to human health and activity the climate of the Amazonian estuary is absolutely the same as in the interior of Amazonia, and has many times been described falsely and in an exaggerated way either as extremely agreeable and healthy or as hostile with unbearable heat and humidity.

Most descriptions are not true, and for the best characterization we may cite Le Cointe: "The climate of Amazonia is warm but not hot, very humid, weakening and enervating, but without being essentially unhealthy". That means that the climate consequently permits the development of a stable and efficient civilization depending on the establishment of a basic economy which takes into account the climatic peculiarities, mainly warmth and humidity.

In the estuarine area of the Amazon we may distinguish three main vegetation zones.

1. The littoral vegetation zone of which the outer limits consist of mangrove of the American, i.e., western, type, with the species *Rhizophora mangle L.*, *Avicennia nitida* Jacq., and *Laguncularia racemosa* Gaertn. Of these species *Avicennia* penetrates farthest into brackish and fresh water. So we find the last specimens of these trees just above Macapá, on the shore of the northern mouth of the Amazon, in the lower *furo* Tajapurú in the Estreitos de Breves, and on the shore of the lower Rio Guamá behind Belém, in front of the Instituto Agronômico do Norte.

The muddy beaches of the mangroves are also occupied by small herbs, the Cyperacea *Spartina brasiliensis* Raddi, etc.

Where there are sand dunes on the ocean shore instead of mangrove swamp, the typical and most frequent plant which grows on them is the Rosacea *Chrysobalanus icaco* L.

On the landward side, the mangrove girdle is often followed by salt marshes before we reach the zone where the influence of the salt water prevails.

All the coastal vegetation is not typically Amazonian but extrahylaean, related to the flora of the Altantic coast of all tropical America.

2. As we have seen, a very large, if not the largest, part of the Amazonian estuary consists of recent alluvial land. This is covered with dense Amazonian jungle, different in its specific composition from the high forest of the Amazonian *terra firme* but similar, though not equal, to the forest of the alluvial floodlands of the lower or upper Amazon, the so-called *várzea*. The difference has its probable cause in a different periodicity of the floods, and so it seems convenient to distinguish these terrains of fluvial alluvions *sensu stricto* with an annual inundation, from the wide stretches of estuarine alluvions. In spite of belonging to the dominion of fresh water, these stretches are still under the influence of the tides, which flood them either twice a day, with every high tide, or only at the spring tides, or even only with the highest water at equinoctial tides.

In the estuary of the Amazon the seasonal floods of the river are not very marked. The level changes caused by the tides are more important than the seasonal high and low waters of the Amazon. Under such conditions, the humidity of the alluvial soil is as constant as possible, and every day the terrain receives new sediments rich in mineral and vegetable detritus. Hence the vegetation is particularly exuberant and rich in essentially tropical forms. Palm trees of various aspects and other big-leaved monocotylous plants (Musaceae, Marantaceae, etc.) dominate the landscape and are much more abundant than in the *várzea* of the lower Amazon which gets the benefit of periodic flooding only once a year, for several months, and then many times even in excess so that it may become prejudicial. This estuarine alluvial forest, as we may call it, exists in its whole exuberance throughout the fresh-water flood lands of the Amazon estuary up to its upper end at the mouth of the Xingú river. It is a true hylaean flora (see Plate XI).

3. Between the coast and the hylaea forest there are numerous open savannahs, called *campos*, in the Amazon estuary. The largest ones occupy half of Marajó Island and are situated along and behind the coast of the Território Federal do Amapá, Brazilian Guiana. Some parts of these *campos* are flooded during the rainy season or some period of it, other parts are not. The parts which are subject to flooding remind one of

the *várzea campos* of the lower Amazon, the others have an extra-hylaean flora with elements which occur in the *cerrado* of Central Brazil, etc. (see Plate XII).

The *campo*-covered area of Marajó of about 20,000 sq. km. is flooded to its greatest extent not twice a day by the tides, as occurs in the western half of that large island, but during some months in the rainy season. It is not river or brackish water which then covers the *campo*, but rain-water which can run off only very slowly through the small rivers and which therefore accumulates on the plate-shaped flat island, so that between February and July the interior of the entire eastern half of Marajó resembles a huge lake. Only a few low islands (called *tesos*) emerge from the rain-water which covers the land to a depth of 1 to 2 metres so that all travel has to be done by boat. The accumulation of rain-water seems to leach out of the inundated soil of Marajó some salts which become dissolved in the water and concentrate highly in the following dry period when considerable evaporation takes place. With the end of the rainy season the land dries up and the water retreats to a few shallow lakes of which the Lago Arari is the largest and most important, because of its fishery and its open connexion to the city of Belém via the Rio Arari. The *campos*, then dry, are used as natural pastures for extensive cattle raising.

Since high *terra firme* terrain with deeper ground water level is scarce inside the Amazonian estuary—occurring mostly outside that area—the high forest of the *terra firme* of the Amazonian hylaea is not often found. The most extensive area of this forest was once the region of the Braganca railroad east of Belém (see Plate XIII), but practically all of it has been cut down.

Before concluding the description of the general features of the delta of the Amazon I should like to include some further data about the water of the Amazonian estuary.

As in every wide funnel-like estuary there is a transitional zone of brackish water of different concentrations between the pure river water and the pure sea-water. That zone varies strongly with the seasons of the year. It has been estimated by Egler and Schwassmann that its beginning is some 200 km. nearer the sea in the rainy season than it is during the dry season.

How far the influence of the brackish water may reach upward into the northern and southern mouth funnels in the different seasons is not exactly known, but it can be taken as certain that it is stronger and farther in the southern estuary, in the Rio Pará, than in the northern estuary by which by far the greatest quantity of Amazon water is launched into the sea.

In the Rio Pará, Egler and Schwassmann observed even in May, during the intense rainy season, brackish water near the left shore in front of the mouth of the Rio Arari.

During the dry season the water in the port of Belém is slightly brackish and at equinoctial high tide, equally in the dry period of the year, a pronounced increase in the chloride content of the Rio Guamá, 8 km. above its mouth behind Belém, has been observed. And the mentioned existence of some single and isolated mangrove trees in the lower part of the Estreitos de Breves may be taken as a sign of a temporary last reach of extremely diluted sea-water up to that zone.

In the northern estuary it has been observed that during equinoctial high tide in the dry season a thin layer of slightly brackish water crept up the river bed at least up to the city of Macapá, while the surface layer was pure fresh water (Sioli, unpublished).

In the rainy season fresh water moves out of the northern mouth also, on the right side along the northern shore of Marajó, but it does not reach the north-eastern corner of that island. At this point an advance of sea-water, which has a rotating movement caused by the tides, reaches the shore, enters the Rio Pará and separates the outflows of this river and the northern mouth funnel.

In the lower courses of all tributaries to the Amazonian estuary the river water is pushed back by each tidal flood, and we see the phenomenon that on river stretches of 200 km. or more the water flows alternately down and up the river. The northern Amazon itself is the only exception to this rule; its tremendous water mass is too strong in its movement for it to be thrown back by the tides. It is only dammed up in its level and slowed down a little in its current.

The tidal lift in front of Belém has an average of 2.40 to 2.85 metres with occasional $\pm$ 3.50 metres during spring tides in the rainy seasons. More or less the same tide levels occur at Macapá, on the northern estuary. In the Estreitos de Breves the $\pm$ 1.50 metre tide lift is not restricted only to the *furos*, but it also floods almost all the islands. At the upper end of the estuary, near the mouth of the Xingú, the height of the tide is still about 1 metre, but from there on the seasonal high water of the river begins to exceed the effect of the tides on the river level.

In some affluents of the Amazonian estuary as well as in some channels between the islands in the northern mouth funnel, there occurs on shallow stretches of the river beds the impressive phenomenon of the so-called *pororoca*, i.e., the formation of a high tidal wave, or rather three consecutive tidal waves. These waves, sometimes 3 or 4 metres in height, roll up the river with overwhelming force, breaking shore trees, turning over and sinking the canoes of the inhabitants and endangering even large motor boats. On deep places of the river bed the waves disappear but reappear at the next shallow place.

The *pororoca* is not a peculiarity of the Amazon estuary alone, similar phenomena occur also in other river mouths, e.g., in the Ganges and in the Seine.

It is probable that the strong turbulent currents

of the *pororoca* contribute much to the instability of the depth conditions in the water courses of the Amazonian estuary, and mainly of those in the northern mouth. No definite maps of the estuary can be made, because the shallows, banks of bottom-drift and of alluvions, which have been known for many years, disappear and other ones are formed in an unforeseen manner at places where some time before there had been deep channels (Le Cointe, 1945).

The *pororoca* and its effect rounds off the picture of a region, the morphology and the dynamics and the life of which have been moulded and determined by the material of half a continent, the climate of the humid equatorial tropics and the forces of the mightiest river and of an ocean in their alternating mutual interactions, a process which will never come to an end.

Résumé

Caractères généraux du delta de l'Amazone (H. Sioli)

L'estuaire de l'Amazone s'étend sur une région dont la superficie est proportionnelle au débit du plus grand fleuve du monde : plus de 100 000 kilomètres carrés, si l'on y inclut les terres formées ou influencées par le fleuve sur les deux rives continentales de son embouchure.

En dépit de ses eaux troubles et riches en sédiments, l'estuaire de l'Amazone ne représente pas, dans l'ensemble, un véritable delta. Un courant marin empêche les sédiments de se déposer dans la mer et les dévie le long de la côte de Guyane, où toute la zone côtière constitue un prolongement des terres alluviales de l'Amazone. L'estuaire s'ouvre sur l'Océan par deux bras séparés par l'île de Marajó. C'est seulement dans la région intérieure de l'estuaire, à l'ouest de cette île, que se forme un véritable delta, là où les eaux de l'Amazone communiquent, par le labyrinthe des Estreitos de Breves, avec celles de ce qu'on est convenu d'appeler le Rio Pará.

La topographie de l'estuaire de l'Amazone s'explique par son histoire géologique récente, et surtout par l'abaissement du niveau de la mer au cours de la période glaciaire et son élévation ultérieure jusqu'au niveau actuel, en liaison sans doute avec certains mouvements verticaux des terres. En conséquence de cette histoire une partie de l'estuaire de l'Amazone est composée de « terre ferme », remontant au pliocène-pleistocène, dont la moitié orientale de Marajó est l'exemple le plus caractéristique; mais la majeure partie est composée d'alluvions récentes qui sont inondées par les courants de marée et non par les crues saisonnières du fleuve comme c'est le cas dans les terres inondables de la vallée inférieure de l'Amazone.

Le climat est chaud mais point torride, très humide, et la pluviosité varie entre 2 000 et près de 3 000 millimètres par an. Le second semestre est plus sec que le premier, le climat correspondant à *Am* de la classification de Köppen. Seul Bélem et ses environs appartiennent à la catégorie *Af* car la différence entre les deux saisons y est beaucoup moins forte que dans le reste de l'estuaire.

On distingue trois grands types de végétation : *a*) formation côtière avec mangroves; *b*) forêts marécageuses denses d'une extrême exubérance; *c*) savanes découvertes, appelées « campos », sujettes ou non à des inondations saisonnières.

La haute forêt de la « terre ferme » amazonienne est rare dans l'estuaire proprement dit, parce qu'il est peu fréquent qu'un sol de « terre ferme » assez élevé repose sur une couche profonde d'eau souterraine.

A la fin, l'auteur décrit les conditions dans lesquelles s'effectue le mélange d'eau douce et d'eau de mer dans l'estuaire de l'Amazone.

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VII

Classification of deltas

Classification des deltas

Main structural features of the great deltas in the territory of the U.S.S.R.

V. V. Egorov

In the U.S.S.R., research is being carried out on various aspects of deltas. From the experience we have gained in this field it is clear that many features of delta landscapes, and their variation in space, are intimately related to their geomorphological foundation. Methods of using deltaic land for the various needs of society can therefore be more successfully selected if the differences in the structure of deltas are borne in mind.

While the importance of geomorphological research concerning deltas is recognized, however, it cannot be claimed that significant results have been achieved in this field. Only certain types of deltas in the U.S.S.R. have been studied in sufficient detail to enable the research workers' findings to be used directly in the organizing of farms. Attention has been concentrated on deltas in arid zones, where the soil is of great value. They have long been used for cotton plantations. Most of these deltas are comparatively simple in structure, approximating to the so-called classic type of delta. They are formed on the banks of non-tidal inland lakes or seas, for example on the banks of the shallow Aral Sea. Less research has been done on other types of deltas and on deltas in other regions.

The various forms of deltas should be grouped according to type, so that better use can be made of the labours of the specialists who are studying deltas, and the problems raised by practical workers may be more quickly solved. An over-all classification of this kind could also be useful to engineers who are making plans for the use of deltas in the national economy. With such a classification as a basis, it would be easier to make use of the experience of soil reclamation which we are gradually accumulating and to apply the results of our experience in one particular case to other similar ones, without any appreciable error. The grouping of the basic types of delta which we propose is as yet something of a working hypothesis, and must be regarded as provisional. Earlier classifications of deltas were made by specialists in the field of hydrology, and reflected their particular interests. They were more suited to the requirements of navigation or the development of the fishing industry, but had little relevance to the problems of reclaiming deltaic land. In accordance with our new objectives, the new classification of deltas takes greater account of the questions of their use in agriculture. Less attention was paid to hydrological factors in drawing it up, but they were not excluded, since they are essential to a proper understanding of geomorphological processes. The converse also is true. Deltaic land, when being formed, has a positive effect on the nature of the river flow, a fact which shows how closely the laws governing both water and the structure of land are interconnected. These brief comments will make the object of this study clear.

Deltas in the U.S.S.R. fall into two broad groups each comprising a number of sub-groups. The first group consists of deltas draining into open seas and therefore subject to the action of the tides. They are found principally in the north of the country, and little has been done to study them or to bring them under cultivation. They are not dealt with in this article. The second group consists of advancing deltas in inland seas, whose development is not affected by the tides. There are many different types of such deltas in the U.S.S.R. and these are discussed below. This class comprises a number of distinct groups, the principal ones being:

1. Conventionally normal advancing deltas. These are formed on stable sea coasts. They are subject to a slight amount of action by sea currents and rough seas.
2. Advancing deltas in inland seas or lakes in desert regions. While they are similar to the first group, there are certain differences.
3. Advancing deltas in regions where the earth's crust is subsiding and the coastline is unstable.
4. Advancing deltas where the shoreline is regressing, i.e., deltas forming in conditions where the level of the body of water is falling, as in the case of the Caspian Sea.

5. Valley or estuarine bay-deltas (delta flood lands). These occur in river valleys which are flooded by the sea.

The proposed classification covers only the deltas of the country's largest rivers. The general features of their structure became known recently, when studies were being made as a basis for a number of projects for reclaiming delta lands for agricultural purposes.

Advancing deltas in inland seas are in many respects similar in structure to the classic Nile delta. Most such deltas in the U.S.S.R. occur in sparsely inhabited regions. They have not been brought under agricultural cultivation to any great extent, nor have they been thoroughly investigated.

There are numerous examples of advancing deltas in seas or lakes in desert regions in the U.S.S.R. Many of them are found in the desert regions of Central Asia, which are surrounded by high mountain formations (the Sir Darya, the Amu Darya, etc.). Because of the desert nature of the land in the lower parts of the basins and the existence of young mountain elevations in the upper reaches of the rivers, the water flow is likely to be saturated with a large amount of particles held in suspension (sediment transport). Where the basins are shallow, this is likely to result in a particularly rapid advance of the delta face. In the case of the Amu Darya, for example, the rate of advance into the shallow Aral Sea is, at times, as much as 2 km. or more a year (in the direction of the main outflow).

The rapid extension of the land area, the plentiful supply of water and the hot climate make conditions very suitable for the development of agriculture. The newly formed sections of such deltas can be quickly sown with cotton, rice, *kenaf* and other crops. The increased interest in the study of these deltas is partly due to this. Much attention is being paid by specialists and practical workers to the reasons for the extreme rapidity with which salinization occurs when these deltas are brought under cultivation. Salinization, moreover, is closely related to the geomorphological structure of deltas. Some details concerning their structure may be of interest. Taking them as a whole, the surface of such deltas is made up of a pattern of regularly repeated surface forms. These similar forms, are, as it were, elementary deltas. Each of these delta elements is formed by a three-component geomorphological complex. As soon as it begins to form as a separate delta fan, sandy spits first develop moving out into the body of water, and act as natural dikes narrowing the river bed. As the alluvium accumulates, they gradually increase in height and widen somewhat on the side away from the channel. The formation of such natural dikes provides the basis of an elementary delta (a delta fan). The further addition of alluvium, which proceeds steadily both in front of the river outfall and over the whole delta space, helps to widen the dikes, and at the same time to form the second component in the complex—flat delta plains beyond the levees along the river channel. These plains are composed of somewhat different fractions of alluvium, with finer particles. In the U.S.S.R. they are sometimes called *polojnye ravniny*—flood-plains—i.e., surfaces inundated by high-flood waters in spring, when the snows melt in the river basin. The third component of the complex which makes up an elementary delta is found where there are small marshy inlets in the delta between adjacent flood-plains. As a rule they are found where two channels are very close together. Marsh plains consisting of alluvium with very fine particles are then formed. They are sometimes called locally, *kultuk* plains (*kultuk* means "a shallow gulf").

In section, the composition of the deposits is seen to be different in each element of the three-component complex. A diagram of a section of alluvium on the natural dike-levees formed beside the river channel shows that, in the lower part, at the base, there are submerged delta deposits (the fore-set beds), in which the sediment consists of finer particles. This sediment contains sea fauna, and it is therefore sometimes attributed to marine deposit. An ill-differentiated series of alluvial material of very coarse texture is deposited immediately in front of the river outfall by the current flowing into the body of water, and accumulates on top of it. The upper part of the series of alluvial deposits at the mouth of the river, carried on to the deposits which constitute the bar or sandbank at the mouth of the river, forms a general complex with the sandy deposits constituting the base of the channel-side dikes (i.e., the spits). The top layers of the section of alluvium in the parts near the river channel are of loam, formed at the period of high floods, when the water overfills the river bed and overflows the banks, leaving part of the material in suspension on the surface of the spits. These sediments are usually considered to be of continental origin.

A similar sequence of deposits is found on the nearby delta plains, but here the particles are finer. Instead of the central layer of sand, there is a comparatively small layer of sandy loam, and the upper layer of loam, in which small seams of clay occur, is thicker.

In areas where there have been marshy inlets, where the third component of the complex (i.e., marsh plains) is formed, all three series of deposits may consist of heavy loam and clay. The upper part of the section of these deposits is usually a layer of gleyed (i.e., formed in the absence of oxygen) marsh clay.

The alluvial deposits in every elementary delta can be differentiated in the same way. Subsequently, they combine to form a single delta plain. It does not take long for an elementary delta to form a separate delta fan. On the Amu Darya, for example, it takes no more than 20 or 30 years.

In the final stages of the formation of an elementary delta, large deltaic gulfs are formed at its sides. When the river breaks its banks, as it constantly does in deltas, the stream of water may reach the banks of the

gulf by a shorter route than the original river bed. In this case, the main stream usually changes its course and quickly fills the gulf with deposits, via the new river bed, and then begins to form a new elementary delta (fan) at the side of the original one. After its advance into the body of water, a similar situation arises again, and gulfs running deep into the land appear along the sides of the new fan. The present sea face of the above-mentioned Amu Darya delta is made up of five such salients or elementary deltas which were formed by the river one after the other.

Experience in the use of the land in such deltas for agricultural purposes shows that, because of the regularity of structure of elementary deltas, a system of treatment which is suited to part of one elementary delta is applicable to other similar elementary deltas without any substantial adjustment.

Advancing deltas in regions where the earth's crust is slowly subsiding are common in the U.S.S.R. (e.g., the deltas of the Kuban, Terek, Kura, and other rivers). They are connected, in most cases, with the great Eurasian area of tectonic sagging—the Aralo—Caspian (Turanian) depression.

Although alluvium is constantly deposited along the sea edge of deltas of this type, they do not show appreciable changes over long periods. All that happens is that the thickness of alluvial deposits increases within approximately the same limits as their bed gradually subsides into the depths of the earth.

An extremely interesting feature of deltas of this type is the occurrence of local incursions of the sea into the delta, in the form of shallow creeks—the consequence of sinking which is not offset by a deposit of alluvium in that area. As in the case of the previous type of delta, the encroachment of the sea promotes the partial reorganization of the hydrographical network. A large part of the river flow is diverted into the creeks which have formed. These quickly fill with alluvium, and the sea edge is then restored. Thereupon, however, the sea again pierces into the delta, in new sections where less alluvium has been deposited. The temporary penetration of sea-water into the delta makes almost no difference to the sequence of deposits, but it leaves behind it lines of sea animals. This sometimes makes it difficult to attribute the entire series of deposits to deltaic action. In form they appear to be marine sediments because of the appearance of the fauna (in occasional layers). The periodic incursions of the sea do, however, have an effect and must be taken into account in considering future agricultural use. The consequent saturation of the sediments with sea-water leads to an over-all increase in the salinity of such deltas in arid zones. Desalination problems are of great importance in these regions.

Advancing deltas in bodies of water whose level is falling and whose coast-line is regressing are of a very special type, and comparatively little study has been made of them. Detailed knowledge of their structure can be obtained only by thorough research. The Volga delta on the northern shores of the Caspian Sea is an example of this type of delta. When the ice of the last great glaciation in Europe melted, the level of the Caspian Sea was about 80 metres higher than at present. Subsequently if fell to a few metres below the present level. While these changes were taking place, the coast-line of the shallow northern part of the Caspian Sea moved very considerably—400 to 500 km. (250 to 300 miles). At the same time, the Volga delta shifted. At present a delta is forming on the Volga at the place where an earlier delta once existed. The river, however, is cutting into it at a broad angle to its former course. The formation of one delta over another but not in exactly the same position has led to the development of an unusually ramified river network in the present delta, with a very large number of both large and small islands. This type of hydrographic network favours the development of the fishing industry, but complicates the use of the delta for agriculture. Moreover, the hydrological situation is extremely complex and heterogeneous, because the rocks composing the deltaic land are constantly—and not entirely regularly—changing, and a large volume of ground water comes from the river beds.

Higher than normal salinity seems to be characteristic of this type of delta, apparently due to the presence of salts in the deposits of earlier deltas which enter into the present processes. Even a short, incomplete list of the special features of this type of delta provides convincing proof of their peculiar—indeed, unique—nature and of the complications involved in utilizing them for agriculture.

Valley or estuarine bay-deltas (flood-land deltas) also have special characteristics, and differ widely from ordinary deltas. They are most commonly found on the northern shores of the Black Sea (on the Don, Dnieper, Dniester and Prut rivers). The tectonic subsidence which has taken place in recent times in the south of Russia, the Ukraine and Moldavia has resulted in the sea penetrating deeply into the lower parts of the river valleys, with the formation of wide estuaries (the local name for which is *liman*). Not only the flood-lands but also parts of the terraces above them—which are very extensive in the East European plain—are submerged.

In the course of the formation of an estuary, the mouth of the river gradually moves back into the flooded valley. The area where the sediments—mainly consisting of various kinds of sand and sandy loam—are deposited at the river mouth moves in the same direction, and these sediments fall on the previous deposits, which have been submerged.

As a result of the continual shifting of the river bed, the deposits at the mouth of the river are covered with yet another layer, consisting of estuarine clays, which accumulate at a distance from the river mouth when it has moved away from the slow-flowing

estuarine waters, which are protected from rough seas. Subsequently, this layer greatly complicates the process of the formation of ground waters in estuarine deltas, since it acts as a waterproof screen between the lower and upper layers of alluvium. The upper layers are formed after the process of subsidence stops or slows down, and the river again begins to deposit sediment in the estuary which has been formed. As the river mouth again advances, a fresh series of various kinds of sandy and loamy sediments is deposited. These deposits do not connect up with the lower deposits except at the apex of the estuarine delta, at the spot where the coastline was formerly stabilized and the river mouth began to advance again. Estuarine clays are not formed in this section. At the conclusion of the deltaic cycle in a particular section, the conditions giving rise to flooding of the river valley recur, and a layer of continental flood-loam accumulates. This accounts for the double name of the flood-land delta. The analogy with flood-lands goes even further. In deltas of this type, as in flood-lands, there may be an inflow of ground-waters from the direction of the original banks which rise above the valley.

This process brings in a further source of accession of salts to the delta. Its effect, however, is limited by the very structure of the delta. The main ground-water flow from the original banks and watersheds occurs in the deep layers and enters the valley from below. The presence of the layer of estuarine clays limits its penetration to the lower series of the alluvium, where it sometimes builds up a slight pressure. Wherever there is a break in the continuity of the layer of clay—for example, where there were once islands—the rising ground waters break through to the surface. This is usually accompanied by the formation of areas with a considerable accumulation of salts. On most of the remaining surface of a flood-land delta, however, the salt accumulation is more moderate than in other types of deltas. The smaller salt accumulation on the surface is apparently due to the lessened effect of the layer of ground water involved in the phenomena of salt accumulation. The layer of clay referred to above acts as a ground-water-proof barrier.

The above list of types of deltas and the brief description given covers the most important kinds of delta in the U.S.S.R. which are used for agricultural purposes or which will be so used in the near future. The so-called dry deltas of rivers which do not flow into permanent bodies of water do not come within the scope of this study, and deserve to be discussed separately. Research on deltas is continuing in the U.S.S.R., and may be expected to lead to new scientific findings.

Résumé

Les caractéristiques principales de la structure des grands deltas de l'URSS (V. V. Egorov)

L'étude d'ensemble de la nature des deltas permet de les utiliser rationnellement pour les divers secteurs de l'économie. Pour étudier les terres deltaïques, il faut d'abord connaître leur structure géomorphologique.

Sur le territoire de l'URSS, les deltas des grands fleuves revêtent des formes diverses. Le rapport étudie des deltas qui débouchent sur des mers intérieures et les groupe en plusieurs catégories :

1. Les deltas saillants qui se forment lorsque le niveau des eaux est stable par rapport à la ligne de base du littoral. Dans cette catégorie, les deltas à progression rapide qui débouchent sur des mers fermées et des lacs de la zone désertique de l'URSS ont été étudiés plus en détail. Les fleuves qui leur donnent naissance ont un important transport solide (turbidité élevée).
2. Les deltas saillants qui se forment dans les zones d'affaissement (de fléchissement) de l'écorce terrestre. Leur progression est de plus en plus lente. La zone marine du delta se caractérise par une stabilité relative malgré le phénomène périodique des petites transgressions marines à l'intérieur du delta, conséquence de l'affaissement. Ces transgressions se produisent sur des terrains où les déblaiements ne sont pas compensés par une accumulation de nouveaux sédiments alluviaux.
3. Les deltas estuariens de fond de baie. Ils se forment dans des vallées submergées (terres deltaïques submersibles). Ils se caractérisent par une alternance très complexe de divers dépôts alluviaux et par un régime particulier de formations deltaïques.
4. Les deltas saillants sur les rives de bassins en régression. Le seul delta de ce groupe qui soit étudié dans le rapport est celui de la Volga, sur les rives de la mer Caspienne.

La connaissance des particularités de structure des diverses catégories de deltas aide les exploitations agricoles à mettre leurs terres en valeur. Les ingénieurs peuvent utiliser leur expérience de la récupération des terres dans les nouveaux deltas, compte tenu de leurs analogies ou de leurs différences.

Malgré ces différences, tous les deltas ont des traits structuraux communs : ils se caractérisent par un régime analogue de formation des dépôts, une certaine communauté de processus hydrogéologiques et géochimiques, comme la salinisation des sols et des eaux souterrains. Ainsi se définissent un certain nombre de principes communs pour l'amélioration des terres deltaïques au service de l'agriculture.

Discussion

J. TRICART : I am very pleased to see a convergence of opinions about the necessity of associating pedology and geomorphology. It appears from various contributions to this symposium that geomorphology, with its rapid and intensive progress these last 20 years, is a necessary basis for pedological studies. Pedology, its methods and results are, on the other hand, a very sound help for modern geomorphology.

Pedology is now known to every one in charge of agricultural management, but this is not yet the case of geomorphology. I think it is, therefore, useful that a recommendation be made by this symposium as regards the interest of geomorphology for practical purposes and the need for including detailed geomorphological studies among the basic research for the establishment of agricultural development programmes.

Tentative classification and comparison with deltas of other climatic regions

A. Volker

INTRODUCTION

The deltaic areas in the humid tropical zone exhibit a great diversity with respect to the general configuration, the pattern of distributaries, the slope from the apex to the sea, the hydrologic régime of the river, the tidal conditions, the relief of the land areas, the composition of the soil and the subsoil, the land utilization and hydraulic development, etc.

A comparative study of deltas can be of interest for both scientific and practical purposes provided that an attempt is made to explain the differences on the basis of the given natural factors of geologic setting, climate, physical conditions of the river basins and tidal conditions.

This involves the consideration of a great number of variables. Whereas no two deltaic areas are absolutely alike, many deltas present common features. Thus a classification may be feasible as a first step towards a better understanding of the manifold and intricate processes of delta formation and physical environment.

It seems logical to extend the classification to deltas in other climatic regions, in particular to semi-arid and temperate zones. In this way the effect of a wide range of conditions can be studied as they appear under extreme conditions.

The object of the present paper is to give an outline of the problem of a classification of deltaic areas in which the various natural factors and basic processes are recognized. The aim is an ambitious one and the paper is an essay on tentative classifications rather than a comprehensive treatment of the subject.

TYPES OF CLASSIFICATION

There is no single classification of deltaic areas; the system to be adopted depends on the object under consideration: geomorphology, pedology, hydrology, etc. With respect to the approach to the problem, an important distinction is between descriptive classification and genetic or causal classification.

Descriptive classification

According to the sphere of interest a descriptive classification of deltas can refer to geomorphologic features, soil composition, hydrologic quantities, natural vegetation, degree of technical development, agricultural pattern, etc.

The significance of a descriptive classification is limited; it is based on features rather than on causal relations. It may form, however, a first approach to the problem and in many cases it is still the only feasible arrangement of available information.

The classifications of deltas found in most handbooks or textbooks on geology or physical geography are of the descriptive geomorphologic type.

Genetic and causal classifications

The objects of the classification may be the same as mentioned above. In a genetic classification, however, the starting point is formed by the factors governing the geomorphologic features, the soil composition, the type of vegetation, etc., and by the basic elements of the hydrologic cycle. A genetic classification explains relationships and shows how under a given set of natural factors various processes will develop.

The present paper deals mainly with the genetic geomorphologic and the causal hydrologic classification of deltaic areas in various climatic regions. Classifications of this type can be of help when making genetic classifications of soils, vegetation and land use in deltaic areas.

A genetic geomorphologic classification aims at relating geomorphologic features to natural factors. The repercussions of changes in these factors on the geomorphologic conditions should also appear from the classification.

A hydrologic classification aims at showing the possibilities, requirements and limitations of a hydraulic development of the delta. There exists a close relation with the geomorphologic classification.

DELTA FORMATION FACTORS AND GEOMORPHOLOGIC FEATURES

Before discussing the problems of the geomorphologic classification it may be useful to summarize the factors of the geomorphologic genesis and the characteristic delta features which should be considered in the classification.

The formation factors can be grouped as follows:

1. Factors related to the river basin.
   (1) River flow and variations in flow.
   (2) Sediment transport (bed load, suspended load and wash load).
   (3) Ice conditions.
2. Factors related to the receiving basin.
   (1) Salinity of the water in the basin.
   (2) Tides and storm surges.
   (3) Swell.
   (4) Littoral drift.
   (5) Foreshore topography.
3. Factors related to the natural boundaries.
   (1) Confining higher areas.
   (2) Barriers ("offshore bars").
4. Factors related to the relative elevation of land and sea.

Characteristic geomorphologic features are:

I. Number and relative size of distributaries
   (1) Few large branches.
   (2) Many distributaries anastomosing near the coast.

II. Configuration and relative elevation of interdistributary areas
   (1) Large not submerged depressions.
   (2) *Valle*, *kultuk* and *plaury*.
   (3) Small lakes and pools.

III. Natural levees
   (1) High narrow ridges.
   (2) Transition levee-backswamp.

For a discussion of the processes of delta formation reference is made to the papers on the sedimentological problems and the tides and currents; here a few remarks will be made in connexion with the general division of deltas.

The most favourable conditions for extensive delta growth are found in lakes, because of the absence of tides, waves and currents. However, the larger deltas are built in the sea for it is there that the largest rivers discharges.

Most of the large deltas are found in inland seas and along the coasts of seas with small tidal ranges. Typical examples are the deltas of the Volga and the Mississippi. The few examples of large deltas in areas with strong tides are the Colorado (spring tidal range, 7.5 metres) and the Irrawaddy (spring tidal range, 5.7 metres). Both rivers have a considerable supply of sediments.

Many rivers do not build up deltas or have not reached the phase of building a sub-aerial delta. A typical example is the Congo where the sediments are collected in deep submarine canyons near the mouth. The great depths of the sea floor may also explain the absence of large deltas along the western coast of South America. In other cases the small sediment yields or the strong tides and waves are responsible for the absence of deltas (estuaries of the Seine, Loire and Gironde).

Subsidence has also an adverse effect on delta extension; however, most of the large deltas in the world are located on subsiding coasts.

Bates (1953; Bates and Freeman, 1953) and Strickland (1940) have described an important feature in the genesis of the interdistributary areas in the tidal zone of a delta. In this zone the natural levees are built up rapidly by the continuous activity of the daily tides. These banks are hardly flooded when the river is in spate and are topped only by the rare storm surges. More inland the high tides do not reach in many cases the same high level as in the coastal strip. The river floods less often attain their maximum level than the tides and since the length of time during which the high levels are sustained is a more important factor than the level to which they may sometimes reach, the coastal strip of deltas with appreciable tides tends to be higher than the inland parts. This explains the occurrence of a chain of depressions in many deltas at some distance from the coastline (chain of *bhils* in the lower portion of the Ganges delta from Calcutta to the east and the low-lying backswamps in the intermediate zone of the delta of the Irrawaddy).

Under favourable climatologic and hydrologic conditions in the lower portions of deltas with tides, peat marshes may develop that build the land surface upward into islands higher than the crests of the natural levees.

EXISTING CLASSIFICATIONS

One of the first classifications was proposed by von Humboldt. He distinguished: oceanic deltas, freshwater deltas and deltas of tributaries. Maximum development of deltas is found with rivers debouching into inland seas (Caspian Sea, Aral Sea), i.e., seas without tides.

Leyll distinguished likewise: deltas in inland lakes, deltas along the coasts of inland seas and oceanic deltas.

Gulliver (1899) defined bay-deltas as areas of filling by sediments of drowned valleys. After depression, the stream in youth builds a delta at the head of the drowned valley, in adolescence it pushes it well forward, and in maturity it has completely driven the sea out of the valley and thus obliterated the initial shoreline of the depression. Thus Gulliver distinguished three types according to the phase of a cycle: young bay-delta, adolescent bay-delta and mature type delta. Special types are the lake bay-deltas, where no ocean currents and tides are present, showing almost complete river intention and the Bonneville bay-deltas, where the lake level has dropped.

As for the other delta types a classification was given based on the ratio of activity between the river and the sea. The examples of shore development by delta growth are arranged in the following series:

Lobate deltas: (a) unilobate (Ebro); (b) multilobate (Donau-Kilia, Volga, Po, Rhône, Mississippi). In this group the action of the river predominates.

Cuspate-lobate deltas (Danube, Fraser, Rhine, Nile). The action of the river in these deltas is still predominant, but the action of the sea prevents the formation of typical lobes.

Cuspate deltas (Tiber, Vistula-Gdansk). The river bed is found in the point of intersection of two curved shorelines which are concave seaward.

Rounded deltas (Rion-Black Sea, Rio Grande). The cuspate extension is prevented by strong shore currents.

Stunted deltas (Cavone-Adriatic Sea, Rio Tinto-Spain Huelva, Rio Turia-Spain Valencia). The river is able only to slightly modify the shoreline.

Blocked streams (Garcia, Senegal). The sea has built a barrier closing the mouth of the river.

The classifications mentioned above are based on the general configuration of deltas as can be seen from a topographic map on a small scale. Important elements such as the pattern of distributaries, the type of backswamps and the development of the natural levees are not considered. The recognition of the ratio of activity between the river and the sea is basically sound, but is of a very general nature.

Classifications comprising all relevant features of deltaic areas can be drawn up only when adequate information on topography, elevation, soil conditions, hydrologic and tidal conditions, etc., is available. For a classification to be truly genetic, understanding of all the processes of delta formation as well as hydraulic and hydrologic processes is necessary. This ideal situation is not yet there but any new classification should be based on the information and knowledge available at the present time.

This principle underlies the classification of deltas recently proposed by Samojlov (1956). His work deals with both estuaries and deltas and is based on the integration of the two elements mentioned earlier. Thus an analysis is given of the various processes in river mouths: hydrodynamic processes, formation of topography and processes of soil formation and biology. This part is followed by short descriptive studies of about sixty estuaries and deltas all over the world.

The main divisions of his classification of estuaries and deltas are given below; further details are mentioned in Table 1. Each of the items of the division is related with typical associated features of the coastline, the coastal zone of the delta and the delta front.

I. Single river branch: (a) with straight river bed; (b) with straight river bed diverted by a sand-bar to a course parallel to the coast; (c) funnel-shaped (tidal funnel-estuary).

II. Two river branches: (a) with subaquatic delta; (b) with emerging delta.

III. Several distributaries: (a) delta in the first stage of filling up of the sea bed (in a space confined by the shores); (b) delta protruding in the sea; (c) lobate delta (under certain conditions secondary delta).

IV. With large interdistributary areas: (a) flats sloping to the sea with large depressions between the elevated beds of the distributaries: (i) with lagoons; (ii) with emerging flats; (b) very gently sloping flats with numerous distributaries ramifying in the coastal zone.

Although this classification starts from descriptive elements rather than from basic factors of delta formation, it opens the way towards a genetic approach. It is demonstrated how, depending on sediment supply, action of swell and available space, a certain type of delta may develop from other types of the table.

A basis for a genetic geomorphologic classification of deltas can also be derived from studies of Bates on a rational theory of delta formation (Bates, 1953; Bates and Freeman, 1953, Cricknay 1955).

Bates considered the jet flow theory where, according to the spreading of the flow, distinction is made between plane jet and axial jet flow, for different ratios of the density of the inflowing water and the density of the water in the basin.

Inflow more dense (hyperpycnal inflow): deltas at the mouths of submarine canyons; deltas in lakes and reservoirs; delta of Hwang-Ho (Yellow River).

The flow pattern is that of plane jet; turbidity currents carry the sediment over considerable distances from the mouth.

Inflow of equal density (homopycnal inflow): deltas in lakes; deltas in small marine embayments.

The flow pattern is that of axial jet with mixing taking place in three dimensions. The river builds a system of shoals and banks at a certain distance from the river mouth with an intermediate branched system of gullies ("spits"). Top, fore and bottom set beds are deposited as described by Gilbert in 1885.

Inflow of lesser density (hypopycnal inflow): practically all major rivers emptying direct into the sea have discharge of the hypopycnal type. With sediment supply increasing from limited to moderate and large the following types will develop: lunate bar forms off the outlet; cuspate type delta; arcuate type delta; bird-foot type delta.

The flow pattern is that of plane jet. The river water will more or less float on the top of the sea water. Since the current will go farther out than in the previous case, deposition of sediments will occur further away from the mouth. The formation of horseshoe shoals is typical for this case.

GENETIC GEOMORPHOLOGIC CLASSIFICATION

The recent classifications of Bates and Samojlov, however different in nature they may be, have provided

TABLE 1. Samojlov's classification of estuaries and deltas[1]

Zone of river mouth	Coastal zone and sea coast or river mouth zone	Coastal waters (sea floor)	Examples
I. *With a single river branch*			
(a) With straight river bed	Large river branch with wide bars (early phase of delta formation, cutting)	Sloping to great depths	Each new river branch formed by cutting in the first period of its activity. A river branch with fixed banks. New Rion (1939), Neufähr mouth of the Vistula (1845), cutting of the Terek at Kargalinskaja (1914), Tiber (Fiumare Grande) Daugava
(b) With straight river bed diverted by a sand barrier to a course parallel to the coast	Large river branch diverted by a barrier to a course parallel to the coast (blocked mouth)	Sloping to great depths	Kamčatka, Bol'šaja, Senegal, some river branches of the Niger, Rio Grande del Norte, the Vistula off Gdansk (up to 1845), Murray
(c) Funnel-shaped (tidal funnel-estuary)	Large river beds, encircling shoals, subaqueous or emerging at low tide	With submarine delta in an early phase, sloping towards great depths	Mezen, Chatanga, Elbe, Weser, Mersey, Clyde, Seine, Loire, Gironde, Hooghly, Megna, Congo, St. Lawrence River (with relict island Orleans), Hudson, Delaware, Potomac, Susquehanna, Magdalene, La Plata, Uruguay
II. *With two river branches*			
(a) With subaqueous delta	Two large river branches, separated by a central submerged shoal formed by waves and currents	With a developing subaqueous delta; sloping to great depths	Amur (two splittings), Columbia, the river branches of many tidal deltas
(b) With emerging delta	Two large river branches, separated by a central shoal, that has become a permanent feature of the relief, i.e., an island	Steeply sloping to great depths, with developed subaqueous delta and break in the slope	Rion, Daugava (in the thirteenth century), Tiber (at the time of the formation of the isle of Sacra), Shatt-el-Arab, Yangtze-Kiang
III. *With several distributaries*			
(a) Delta in the first phase of the filling up of the sea floor (in a space relatively confined by the shores)	Large river branches building horseshoe-shaped shoals in the coastal waters separated by gullies and sand bars. These shoals become islands with small lakes (in case of small amounts of wash load in the river) or continuous islands (in case of considerable amounts of solids)	Steeply sloping to great depths with large river-bed gullies and break in the slope	Dnieper, Don, Northern Dvina, Pečora, Ob, Yenisey, Lena, Yana, Indigirka, Kolyma, Neva (?), Rhine, Mackenzie, Amazon
(b) Delta protruding into the sea			Lena, Yukon, Zambezi, Niger

1. The characteristics of the corresponding types of the sea floors are approximate owing to the shortage of sufficiently accurate cartographic data. The lagoon coastal zones (Dniester, Niemen, Oder, Nogat) have not been considered as a special type, since the sand barriers forming the lagoon are not directly related to the sediment of the relevant rivers.

Zone of river mouth	Coastal zone and sea coast or river mouth zone	Coastal waters (sea floor)	Examples
(c) Lobate delta (under certain conditions secondary delta)	Relatively large river branches with wide sand bars commonly splitting nad forming a central shoal by cutting of the banks; on the side not exposed to the wind a breaker barrier is often built up from the alluvial deposits which did not reach the body of the delta	With break in the slope, transition to shallow water with unstable gullies and sloping towards great depths	Kura, Ural, Dniester, Selenga, Kilia delta of the Danube, Po, Ebro, Hwang Ho, Mississippi
IV. *With large inter-distributary areas*			
(a) Flats sloping to the sea with large depressions between the elevated beds of the distributaries	Large river branches spaced widely apart; if they remain stable for considerable periods of time breaker barriers are formed between the branches ligating limans.	With break in the slope	
(i) With lagoon coast or with lagoon coastal zone			Kuban, Nile, Danube (with "cells" of the relief not yet filled up by alluvial deposits).
(ii) With a preponderance of emerging flats	Large river branches spaced widely apart dying off by frequent cutting of river beds in the area of the river mouth; they are separated from one another by sand banks with breaker barriers (coastal waters with break in the slope) or by subaquatic vegetation (shallow coastal waters)	Transition to shallow waters	Amu-Darya, Syr-Darya, Terek, Colorado (northern), Indus, Mekong, Irrawaddy
(b) Very gently sloping flats with numerous distributaries ramifying in the coastal zone of the delta	As well as some large river branches there are very small river branches with long narrow barriers in the mouths, ligating shallow embayments (*kultuks*), becoming river lakes and later shallow and flat islands, surrounded by the elevation of the natural levee; the bisection of the river branches mainly takes place by twin cuttings of the barrier system	With shallow water, with delta front gullies, tracing the future network of river branches along the coast	Volga, eastern part of the Lena delta, in the near future the deltas of the Don and the Dnieper, Orinoco (?), Niemen (?), Nogat delta of the Vistula (?), Parana

Source : I. V. Samojlov, *Die Flussmündungen*, Gotha, 1956 (translated from Russian and German).

a solid basis for a genetic geomorphologic classification.

The classification following from Bates' theory arranges the deltas according to the ratio between density of inflowing water and density of water in the basin. Although his quantitative deductions have been criticized (Crickmay, 1955), it must be true that the mode of deposition of sediments on the delta front is greatly influenced by the density ratio. It can be assumed, however, that as far as the geomorphologic features of the inland areas of the delta are concerned, the amount of sediment, the tidal range and the type of flood have a more direct effect.

The cases mentioned in this paper are limited to Bates' group of inflow of lesser density, covering the oceanic deltas and the deltas along inland seas. All the examples mentioned in Samojlov's classification also refer to this very common category.

Samojlov's classification deals with both estuaries and deltas and covers the whole sequence of formation of bars, bifurcation of the main channel, development

of a subaquatic delta and growth of the sub-aerial delta. The deltas proper are found in the groups II (b), III and IV of Table 1.

The ideal genetic geomorphologic classification would have the natural factors of formation mentioned in the previous paragraph as entrances. The classification should tell how, depending on the relative magnitude of the relevant quantities, a delta will grow naturally, what system of river branches will develop, what type of interdistributary areas will be built up, etc. It would then be possible to indicate along which lines in a certain stage of the natural formation process a given delta would tend to grow further and what would be the effect of a natural or artificial change in one or several of the formation factors on the further development on a long term. Such a classification would be of great practical value both for the reconstruction of the geological history and for the prediction of future conditions.

The great number of formation factors, the intricate processes of the combined action of these factors and their different nature are major obstacles in this approach. Another difficulty is that in one and the same delta different parts show different developments. Scruton (1958), distinguishes in the delta-building a sequence consisting of constructional and destructional phases. This is due to the shifting of the river for a shorter route to the sea when it becomes over-elongated. The recently built delta is abandoned and modified by compaction coupled with marine wave and current action. Typical examples are found in the delta of the Mississippi (Plaquemines-St. Bernard area of destruction), the Donau delta (Kilia branch as recent constructional area) and the delta of the Rhone (retreat of the Petit-Rhone area), (van Straaten, 1959). The older parts of these deltas and of many others consist of a system of imbricating deltas.

The sequence in the delta formation poses a problem for the classification. In one and the same delta different zones can be distinguished entering into different groups of the classification. This is also found in Samojlov's classification with respect to the deltas of the Vistula, the Danube and the Lena and it certainly applies to many other deltas too. Obviously classification is mainly based on the features of the active part of the delta but in many cases a further distinction is necessary.

Since it is practically impossible to introduce all the formation factors as variables, it seems appropriate to consider only a few and to account for the effect

TABLE 2. Characteristic features of deltas

Name of river	Slope from the apex	Geomorphologic features			Spring tidal ranges (metres)	Sediment yield (10^6 ton)	Yield (cu. km.)	Sediment concentration (kg. per cu. metres)
		Branches	Interdistributary areas	Levees				
Terek	5×10^{-4}	I.1	II.1	III.1	—	26	11	2.4
Colorado	3×10^{-4}	I.1	II.I	III.1	7.5	160	20	8.0
Amu Darya	2×10^{-4}	I.1	II.1	III.1	—	100	49	2.0
Kiso [1]	$10^{-3} - 10^{-5}$	I.1	II.1	III.1	2.0	?	7	?
Cho-Shui [1]	10^{-3}	I.1	II.1	III.1	4	59	5	11.8
Nile	2×10^{-4}	I.1	II.1	III.2	—	54	70	0.77
Indus	1×10^{-4}	I.1	II.1	III.1	2.3	400	175	2.3
Chao-Phya	1×10^{-4}	I.1	II.1	III.2	2.6	12	31	0.39
Rhine	9×10^{-5}	I.1	II.1	III.2	3	5	70	0.07
Red River	9×10^{-5}	I.1	II.1	III.2	4	130	76	1.7
Niger	6×10^{-5}	I.1, I.2	II.1	III.2	—	67	293	0.23
Syr Darya	5×10^{-5}	I.1	II.3	III.1	—	12	14	0.86
Irrawaddy	5×10^{-5}	I.1, I.2	II.1	III.2	5.7	350	428	0.82
Don	5×10^{-5}	I.2	II.1, II.3	III.2	—	6.5	28	0.23
Po	5×10^{-5}	I.2	II.2	III.2	—	18	49	0.37
Mekong	3×10^{-5}	I.1	II.1	III.2	4	80	378	0.21
Volga	3×10^{-5}	I.2	II.2	III.2	—	26	255	0.10
Dnieper	3×10^{-5}	I.1, I.2	II.3	III.2	—	1	53	0.019
Pearl River	3×10^{-5}	I.1. I.2	II.1	III.2	3	28	325	0.086
Mississippi	2×10^{-5}	I.2	II.3	III.2	0.6	730	590	1.2
Amazon	2×10^{-5}	I.2	II.3	absent	3.2	1 000	3 160	0.32
Lena	1×10^{-5}	I.2	II.3	III.2	0.2	12	490	0.024
Parana	1×10^{-5}	I.2	II.3	III.2	0.6	96	600	0.16
Danube (Kilia)	—	I.2	II.2	III.3	—	58	141	0.41
Danube (Izmail)	—	I.2	II.2	III.2	—	83	201	0.41

1. Kiso (Japan, Nagoya) and Cho-Shui (Taiwan) are examples of "short" rivers in an early stage of delta formation.

of the others by a compound feature; for example, the over-all slope of the land in the delta from the apex to the sea. This slope primarily depends on the type of sediment, the sea-floor configuration, the subsidence in different parts of the delta and the sequences in the formation. An arrangement of deltas according to this slope (see Table 2) shows that the range is considerable; it actually varies between 5×10^{-4} (5 metres per 10 km.) to 1×10^{-5} (1 metre per 100 km.). Most of the deltas in the semi-arid zone belong to this type as well as deltas formed by "short" rivers, i.e., rivers that debouch in a deep sea before their slope can flatten out. In both cases the coarseness of the sediments seems to be the major factor.

It may be seen from Table 2 that many geomorphologic features mentioned above are associated with the degree of slope. Thus the river system with a few large distributaries (Table 2, I. 1) prevails in the group of deltas with slopes between 5×10^{-5} and 5×10^{-4}. In the same group are found the deltas with large non-submerged interdistributary areas. (II. 1). With slopes from the apex to the sea smaller than around 5×10^{-5}, the river splits up into a greater number of branches (I. 2), especially in the coastal strip. The interdistributary areas consist of *valle* of swamps and small pools (II. 2 and II. 3). The natural levees likewise change from group III. 1 to III. 2.

The classification given in the table is descriptive rather than genetic but it shows related features. The slope from the apex to the sea is an important factor in the hydrologic conditions of the delta with respect to flood discharges, bed load and bed position, sea-water intrusion in the open estuaries, etc.

The data on deltas mentioned in Table 2 can be portrayed in three-dimensional diagrams plotting the magnitudes of the tides, the sediment yield or the sediment concentration and the slopes along the three axis. Each delta is thus represented by a point in the spatial diagram.

Such a diagram shows the considerable range of conditions occurring in various deltas but it does not solve the problem of a genetic geomorphologic classification from which, for instance, the effect of a change in the sediment régime of the feeding river could be deduced. This problem can be tackled only by consideration of the specific conditions of each particular delta for which much more information must be available than can be expressed by a few general factors.

HYDROLOGIC CLASSIFICATION

A hydrologic classification of deltaic areas considers hydrologic features like water stages, flooding, salinity conditions of estuaries and inland waters, erosion and deposition, etc., and shows the relation between these features and elements of sea, river and climate. The relation with the geomorphologic classification is obvious but in the hydrologic classification the geomorphologic features are given and attention is focused on the conditions for the hydraulic development.

The factors to be introduced in a hydrologic classification can be grouped as follows:

I. Factors related to the receiving basin
   1. Tidal régime (tidal range and tidal currents).
   2. Storm surges (magnitude and frequency of occurrence).
   3. Waves (magnitude, frequency and direction).
   4. Salinity of the water in the basin.

II. Factors related to the feeder river
   5. Flood régime (flashy and gentle floods).
   6. Sediment régime.
   7. Minimum flow.

III. Factors related to the climate
   8. Humid tropical.
   9. Semi-arid.
   10. Temperate.

The hydraulic problems involving consideration of one or several of these factors pertain to

A. Protection against sea floods (1, 2 and 3).
B. Protection against river floods (5 and 6).
C. River training (5 and 6).
D. Salinity control (4, 7 and III).

For long-term development attention has also to be paid to the effect of subsidence, the changes (natural or artificial) in the régime of the feeder river, and the effects of human interference in the delta.

According to the climatic type of the region, the hydrologic problems of deltas can be classified as follows:

1. Deltas in temperate humid zones
   A. Some deltas in the temperate zone bordering on shallow seas are exposed to abnormally high sea-levels generated by storm surges.
   B. The floods are generally moderate owing to low rainfall intensities on the river basin; even in relatively small river basins they show gentle rises and falls.
   C. On the whole the sediment load of the rivers is small owing to the low erodibility and small rainfall intensities in the catchment basin. The rivers are relatively stable, but river training is still necessary in view of the maintenance of flood protection works.
   D. Although the river flow shows a seasonal variation, there are no periods of prolonged drought with zero flow. Thus the salt-water intrusion in the open estuaries will remain within certain limits from the coastline.

   In the interdistributary areas in the coastal zone that may be flooded at abnormally high tides, a certain salinization of the surface water and the soil will occur. Since the evaporation rate is low and periods of drought are short, the salinization is not very intense. In the cold and rainy season, much of the salt will be flushed away. The serious salinity problems in the delta of the Rhine

are mainly due to artificial sources of salt (seepage of saline ground water in reclaimed low-lying areas, entrance of sea-water through ship locks and salt discharge by waste disposal of the Rhine).

2. Deltas in semi-arid zones
   A. Most of the deltas in the semi-arid zone are not exposed to the effect of storm surges.
   B. The river floods are generally flashy owing to high rainfall intensities and considerable surface run-off. The classical example of the Nile delta as a delta in a semi-arid zone can better be classified in a separate group (see 4 below).
   C. In connexion with the river régime, the climate and the erodibility of the soil, the sediment load of the rivers is considerable. The river beds are silting up rapidly and the channels are frequently shifting. River training is a difficult and costly undertaking and the same applies to flood protection.
   D. The salinity conditions are extreme and thus salinity control is the major hydrologic problem. During the long period with minimum river flow the saline water from the sea can penetrate far upstream and is checked only by the relatively steep slope. This supply and the high evaporation rate are responsible for the pronounced salinization features in the interdistributary areas. Tricart (1955, 1961) has described the salt problems in the delta of the Senegal. He distinguishes residual salt dating from former geological periods and remaining in a circuit, and present sources of salt continuously supplying new salt to the system. His recommendation to evaluate the sources and salt circulation quantitatively when contemplating improvement works should be applied to each delta.
3. Deltas in the humid tropical zone.
   A. The occurrence of storm surges and their bearing upon the hydrologic conditions of the coast have been discussed in other papers.
   B. The type of river flood (flashy or gentle) determines whether flood protection by embankments is an absolute necessity for the use of the land as paddy fields or not.
   C. The sediment concentration of the river water is lower than in the semi-arid zones with a greater portion of silt.
   D. The salinity conditions in the deltas depend to a large extent on the annual distribution of river flow and rainfall. In tropical areas with a prolonged dry season like in most of the deltaic areas in South-East Asia, salt intrusion from the sea occurs as soon as the discharge falls below a certain limit, depending on the location. During the ensuing dry season, with high evaporation rates, concentration of salt takes place in the surface waters and in the soil. Because of the high rainfall in the wet season and the floods, most of the salt will be flushed away and thus salinity hardly poses a problem during the growing season for single cropping. Conditions are different, however, should the land be used for irrigated crops during the dry season.
4. Zonal deltas.
   The rivers of many large deltas have their catchment areas in a climate zone different from the one where the delta is situated. Striking examples are the deltas of the Nile and the Senegal and in general many deltas in the arid zone.

The significance of the geomorphologic features for the hydraulic development can hardly be over-estimated. This applies to all deltas in the various climatic zones. Striking examples are the situation and structure of present and former natural levees and beach ridges for the alignment of embankments and roads and the location of built-up areas, the configuration of backswamps for the alignment of drainage and irrigation canals, the origin of the salt in view of salinity control, etc. There is hardly any place where hydrologic and geomorphologic features are so closely associated as in deltaic areas.

Résumé

Essai de classification et de comparaison avec les deltas d'autres régions climatiques (A. Volker)

Les deltas peuvent être classés en fonction de considérations relevant de diverses disciplines : géomorphologie, pédologie, hydrologie, biologie, etc.

Les classifications descriptives sont utiles dans la mesure où elles constituent une première mise en ordre des données disponibles, mais elles doivent être suivies de classifications génétiques et causales expliquant l'interrelation et l'évolution des phénomènes.

Cette étude a trait à la classification géomorphologique-génétique et à la classification hydrologique.

L'examen des nombreux facteurs qui interviennent dans la genèse géomorphologique fait ressortir les problèmes que pose l'établissement d'une classification géomorphologique. Ces facteurs concernent le fleuve, la mer — ou le lac — où il se jette, les frontières naturelles et l'élévation relative du terrain et de la mer. C'est en fonction de ces facteurs que l'on expliquera les caractéristiques géomorphologiques telles que la disposition des bras du fleuve, la configuration des

zones qui les séparent et la constitution des levées naturelles.

Les classifications géomorphologiques descriptives auxquelles on se réfère couramment restent fondées sur le modèle établi par Gulliver (1899). Selon lui, le delta résulte de l'action relative du fleuve, en tant qu'agent constructeur, et de la mer, comme agent destructeur. Il ne considère que la forme générale du delta et néglige les autres éléments géomorphologiques.

La classification de Samojlov (1956) qui englobe les estuaires et les deltas marque une nouvelle étape en la matière (tableau 1). Elle repose sur l'analyse des divers phénomènes et sur des données très complètes concernant les deltas du monde entier. Tout en étant fondée sur des éléments descriptifs, cette classification géomorphologique fait état de facteurs génétiques.

Dans la classification inspirée de la théorie de Bates (1953), les deltas sont répartis en fonction du rapport entre la densité des eaux affluentes et la densité de l'eau du bassin.

La classification idéale de caractère géomorphologique-génétique doit être fondée sur les facteurs naturels de formation. Il sera ainsi possible d'indiquer l'évolution future d'un delta et l'effet d'un changement, d'origine naturelle ou artificielle, dans l'un des facteurs de formation.

Le grand nombre des facteurs de formation et les conditions très diverses des différentes parties d'un seul et même delta sont les principaux obstacles à l'établissement d'une classification selon cette méthode. Il faut souvent distinguer les zones de construction des zones de destruction.

Une caractéristique des régions deltaïques qui dépend de nombreux facteurs géomorphologiques est la pente moyenne du terrain depuis le sommet du delta jusqu'à la mer (tableau 2). La pente joue un rôle important dans la situation hydrologique d'un delta.

Des pentes relativement accentuées (de l'ordre de 5×10^{-4} et davantage) existent dans les deltas de la zone aride et dans les deltas qui commencent à se former.

Le nombre des bras du delta et la configuration des zones qui les séparent semblent dépendre de la pente. Lorsqu'elle est inférieure à 5×10^{-5} environ, le fleuve se scinde en un plus grand nombre de bras et les zones de terre acquièrent des caractères correspondants qui sont typiques.

La classification hydrologique est fondée sur trois groupes de facteurs : les facteurs hydrographiques concernant le bassin de réception, les facteurs hydrologiques concernant le fleuve qui l'alimente et les facteurs climatologiques.

Pour ce qui est des quatre principales catégories de problèmes hydrauliques (protection contre la submersion par la mer, protection contre l'inondation par le fleuve, aménagement des cours d'eau et réduction de la salinité) on constate des différences typiques entre les deltas des diverses régions climatiques.

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Concluding remarks

F. R. Fosberg

INTRODUCTION

I feel both flattered and dismayed to be asked to offer some concluding remarks to this symposium. I have little experience with deltas and little competence in most of the fields treated in the discussions. However, one should perhaps never neglect an opportunity to express such ideas as one may have to a captive audience. I have been associated with the Unesco Humid Tropics Research Programme since its beginning in Kandy (Ceylon), eight years ago, and am still chairman of its advisory committee. Since this may well be my last opportunity to express myself in this capacity, I am about to take advantage of my position and express several things which, though they may seem extraneous, yet have a bearing on what we are trying to do in this symposium.

In order to perceive some central idea in the mass of papers that have been offered, and to draw any valid general conclusions from them, I find it desirable, first, to say a few things about the Humid Tropics Programme, its nature and scope. First I may say that we have tried to keep the programme within the area of fundamental science, leaving the practical applications to appropriate other United Nations agencies and to the national programmes in the area. Secondly, we have operated within the broad field of an interdisciplinary approach to understanding the humid tropical ecosystem.

We have worked, not as an operating agency, but as a source of ideas and as a catalyst. We have devoted special attention to the availability of facilities for scientific work, to reviewing and summing up available information in pertinent fields of knowledge, and the presentation of this in the form of international symposia, such as this one. Our emphasis has been on bringing together people of varied backgrounds, interests and experience to consider questions and complexes of questions that remain unanswered if approached from within particular fields. The nature of the humid tropical ecosystem is so complex that we can only hope to gain any understanding of it by bringing to bear the competence and methods of all appropriate scientific disciplines. Hence the nature of this symposium and the diversity of those involved in it.

It is my understanding that the motivation for this symposium on scientific problems of humid tropical deltas grew out of the need for basic information that would be of use in the ECAFE Symposium on Flood Control, Reclamation, Utilization and Development of Deltaic Areas. I take it that what are needed are strictly scientific information and ecological understanding. Although these are unfortunately not a part of the usual equipment of engineers, they are essential to the effective and beneficial performance of many of their tasks. I do not take it as part of the directive that we in any way attempt to do the engineers' work for them. It would seem that our direct relations with engineers should be to provide them with basic information and cautions about the ecological implications and long-term effects of their projects.

After the outline for the symposium was formulated, the emphasis seems to have shifted somewhat, until we now seem to be as much concerned with the engineering and other practical aspects as with the scientific ones. When I discovered this, I was somewhat disturbed at first. Then I realized that this was the opportunity I have long wanted to expose engineers to biological and especially ecological ideas and patterns of thinking. This could result in a better understanding on their part of possible long-term consequences of engineering undertakings. It might even bring about a beginning toward the utilization of ecological and other biological data in their thinking, just as now physical, geological and hydrological information is used. If this could happen, an important step would have been taken toward a more intelligent planning of public works. At least, some deleterious long-term consequences might be foreseen and avoided.

So I rather welcomed the association, on this

programme, of engineers and practical hydrologists with scientific geomorphologists and hydrologists, pedologists, biologists, and even sociologists. It is perhaps the last named category in which we are most deficient.

I was asked to bring together the conclusions of the symposium. This is not at all easy. What conclusions can be drawn from even a very careful description of a particular example of a phenomenon, except that it exists? It seems more logical to consider the matter by subject areas than by papers. Inevitably this will involve the exercise of personal judgement on my part. Even more important than particular subject areas are the interrelations and interactions between them, and their significance.

My first judgement will be to eliminate consideration of matters with no bearing or only slight bearing on the subject of the symposium. Further, emphasis will be placed on matters of scientific rather than engineering or agricultural interest. It will be clear, of course, that my emphasis need not be the final one. Discussion will serve to bring out any changes that are desired by the participants in the symposium.

Although not an entirely successful arrangement, the breakdown by subject areas appearing in the final programme may largely be accepted here. However, the discussion may be facilitated by the removal of pedology from geomorphology and sedimentation into a separate category and by the substitution of geology for sedimentation as a more inclusive term to permit discussion of several phenomena that are basically geological, especially subsidence.

This leaves us with the following outline: Geology and geomorphology, Pedology, Hydrology, Vegetation, Biology, Human influence.

The arrangement of these fields leaves much to be desired, but corresponds roughly with the order in which the discussion took place.

The most conspicuous deficiency in the symposium, as presented, was the lack of an introductory paper, giving the general characteristics of deltas, their distribution in the world and the special features of humid tropical ones. If such a paper had been prepared well ahead of time and placed in the hands of all participants, much lack of orientation, semantic confusion and repetition, might have been avoided.

As a great help for further approaches to problems of deltas, the compilation of bibliographies on deltaic areas is strongly recommended and should be initiated by Unesco.

GEOLOGY AND GEOMORPHOLOGY

Separating these two fields, as is commonly done in Europe, seems rather artificial. Erosion and sedimentation, as well as tectonic or isostatic subsidence, are geological processes, but their results are changes in the physiography of the area concerned.

The surface features of deltas are perhaps the best known of all delta phenomena. Delta morphology and its fluctuations can almost be predicted if the essential facts are available on river régime, sedimentation, pre-existing terrain and coastal morphology, tides and, especially, slope. Complications are introduced by subsidence, due either to compaction or isostatic adjustment, as well as by storm surges. Historical geological factors, especially Pleistocene and Recent sea-level and climatic changes add further complexity. It seems that the present surface features of existing deltas do not date very far back, geologically.

The essential function of aerial photography and of dynamic geomorphological maps in both scientific and applied studies of deltas was convincingly demonstrated. It seems clear that enormous savings of time, as well as much greater accuracy and completeness in geomorphological work can be achieved by the use of these techniques. Of especial value in the study of the coastal areas of deltas is the combined use of infrared and coloured aerial photography, and it is recommended that combinations of these new techniques be used in further aerial photograph coverings.

The role of bar-formation at river mouths in delta-building and the mechanics of this process were demonstrated. The effects of varying current velocities, formation of multiple channels, interaction of fresh and salt water, tides, wind waves, long-shore currents, and even of the Coriolis force, were shown to be important in the patterns of sedimentation and the resulting forms of deltas.

Classification of deltas received especial consideration. Most previous classifications have been purely descriptive, resulting in logical arrangements, based on one or more sets of features. In 1956, a genetic classification was formulated by I. V. Samojlov, which served as a basis for a further elaborated genetic scheme, presented as the climax of this symposium. The philosophy behind it was elaborated, showing how, indeed, all of the dynamic systems contributing to involved delta-building must be considered in a truly genetic classification. The result is truly more than simply a classification. It is a synthesis of the available geomorphologic knowledge and experience, so much so as almost to merit the term *tour de force*. It should long serve as a model for genetic classifications of other geomorphological phenomena.

One further observation may be pertinent. Remarkably little attention was given in the symposium to the role of Pleistocene and Post-Pleistocene climatic and sea-level changes in the genesis and present morphology of deltas.

PEDOLOGY

The study of soils is clearly enough demarcated to be treated separately from geomorphology, though at times it may seem so confused with agriculture as to have no clear identity of its own. The agricultural

aspect, however, is probably best called edaphology rather than pedology.

It was shown in the symposium that delta soils strongly reflect the character of the rock complexes in the river drainage basins that supply the sediments. Old, well-drained delta soils, as with other aerated tropical soils, accumulate little humus. Low nutrient status, with excessive leaching and lessivage accompany this low humus content. Low fertility and marginal agricultural use are evident on older delta terraces. Poorly drained, waterlogged soils are likely to build up a high sulphide content. If the water table is lowered and the soils aerated, the sulphides may oxidize and sulphuric acid may result, producing the highly acid "kosh" or "cat-clay" soils found in many deltas. Deep humus and peat soils are found in delta basins that are not or are seldom flooded by silty water.

The dominant fact about younger or lower delta soils is the annual accretion of silt brought from the drainage basins by the floods and spread over the surface of the soil. This tends to maintain the soils in an immature but highly fertile condition. Profile development is not observed in these younger delta soils.

Salinity seems fairly general in the seaward portions of most tropical deltas, especially in areas where storms are common.

HYDROLOGY

Water is the dominant element of the physical environment of deltas. In the humid tropics atmospheric humidity is an added consideration in this field, though not discussed much by the hydrologists. In the symposium relatively little attention was paid to scientific hydrology, perhaps because of a preoccupation with problems of irrigation and flood control—subjects presumably already taken care of by the ECAFE symposium.

Some emphasis, but perhaps not enough, was placed on the relation between excess surface water and denudation in the drainage basins. A quantitative formula was developed for the increase in salinity of the ground water from the head to the seaward part of a delta due strictly to evapotranspiration. The scarcity of water-quality studies in deltas was stressed, with a plea that this be remedied.

The complete interdependence of ground-water and surface-water phenomena was demonstrated and the suggestion made that ground-water hydrology and surface-water hydrology no longer be regarded as separate disciplines.

The function of floods in renewing the fertility of the soil was a recurring theme in the discussion, but did not seem to be regarded as of vital importance by the engineers. Flood control seemed to be the dominating motif in the engineering considerations. Little concern seemed to be manifest for the desirability of having engineering enable people to live with and benefit by the floods, rather than control and eliminate them.

The effects of the sea in creating a situation of fluctuating salinity, or estuarine condition, is one of the basic hydrological facts of marine deltas. Except for storm surge, causing catastrophic changes, this is a normal condition. The natural vegetation is exceptionally well adapted to it. It seems surprising that almost no attention was given in the symposium to the possibility of adaptation of man's activities to this situation. The only such suggestion was that investigation be made of possible salt-tolerant crop plants, or rather of the actual salt tolerance of existing crop plants. It might also be suggested that we investigate the productivity and ecological function of this zone. Perhaps it would be better to utilize it as it is, rather than to modify it. This is usually the active part of the delta, still building up. What is the relation of this zone to the marine resources of the region? We do not know. At present, the construction of embankments and establishment of agriculture are all that the planners can think of, even though this involves enormous initial expenditure and continual upkeep.

Defence against storm sturges is usually accomplished by embankments. It was brought out, however, that a strip of mangrove vegetation may accomplish this protection with no out-of-pocket expenditure.

The following recommendations were made for consideration by steering bodies of the forthcoming Unesco Hydrological Decade:

1. Establishment of a basic network of hydrological observations in all developing deltaic areas on a standard basis.
2. Joint programmes of countries on developmental activities in deltaic areas to be encouraged on a voluntary basis.
3. Representative sample areas to be demarcated and utilized for detailed study of water management.
4. Some delta areas to be left in their natural state as controls for assessing the success of development work.
5. Geomorphological studies of deltas to be undertaken on the basis of detailed geomorphological mapping.
6. Establishment of dynamic balances of sedimentation and erosion in deltaic areas.

VEGETATION

It is commonly observed that the natural vegetation of humid tropical deltas is usually, but not always, woody. In the saline portions mangrove swamps are the typical vegetation. Upstream freshwater swamps and peat swamps are found, and on natural levees, something like the normal broad-leaf forest of the region. Under certain extreme or peculiar conditions, especially of very high salinity, herbaceous vegetation may occur, or none at all. Only a beginning has been made toward an understanding of the physiological

adaptations that enable plants to cope with this unusual and rigorous environment. Further studies in this direction are strongly recommended. The symposium makes the concrete recommendation that Unesco encourage investigations into the salt tolerance of plants that grow in deltas or that might be grown there.

Geomorphologically, the role of natural vegetation seems to be in binding and stabilizing the otherwise loose sediments and in contributing materially to the substance of these sediments.

Anthropogenous vegetation, adapted to other purposes, principally agriculture, reflects the delta pattern much less clearly than does natural vegetation and serves the function of sediment stabilization much less well. It may be added that in delta areas that have been long subject to human occupation, the nature of the original vegetation is often completely unknown. The existence of peat beds, as well as other bedded sediments, suggests that palynological and other paleobotanical studies would clear up this lack of information, at least to some extent. Meanwhile, immediate, detailed floristic and vegetational surveys should be made of all areas of tropical deltas that still retain any natural vegetation, since such vegetation is disappearing or changing with distressing rapidity.

BIOLOGY

Compared with the scientific investigations of delta geomorphology, hydrology and agriculture, the amount of biological work that has been done on humid tropical deltas is infinitesimal. And yet the complexity of delta biology is infinitely greater than that of the above-mentioned fields. Thus, agricultural and engineering modification of deltas has taken place in an almost complete absence of knowledge or understanding of delta biology. It cannot be stated that this does, but certainly it could, lead to an impoverishment of delta regions, even as a human habitat.

The single example presented in the symposium of an investigation of a small invertebrate animal group, the shipworms, illustrated the fact that not even the identities of most delta animals are known as yet. It seems clear that most of the delta biology will never be known, unless a deliberate policy is adopted of setting aside adequate delta reserves or natural areas. These should preferably be sectors of as undisturbed areas as remain, extending from the heads of the deltas to the sea. These areas must be protected against exploitation, so that they may provide areas for future studies, as well as refuges where at least some of the little-known delta biota may continue to live. Such areas would also serve as examples for future study of the geomorphic features of deltas, as well as check areas or controls against which activities such as engineering and soil management may be judged. Such preserved areas would also provide a continuing opportunity to check increases or decreases in the productivity of deltas under different systems of management. It is hoped that the developing countries will grasp in a shorter time what it took northern countries all too long to learn—that natural areas are vital facilities for many branches of biology. If such areas are to be set aside it must be now, while something remains to be preserved.

It is recommended that Unesco should promote, on an international basis, detailed investigations in some sample areas, left in their natural state of vegetation, biology, microbiology, pedology, etc., and to compare the natural development with the development under artificial conditions.

HUMAN INFLUENCE

Most of the great deltas in the humid tropics have been, at least to some extent, occupied by man for many millenia. Some of the early civilizations arose on deltaic areas. Hence human influence on deltas is of long standing. Some of the modifications, though slight, had profound and far-reaching effects. The influence was not all in one direction, as the delta environment also exerted a profound effect on the human cultures that evolved there. The processes involved, up until relatively recently, were slow enough that satisfactory equilibria were maintained.

Modern technology has speeded up the changes until any equilibria are now unlikely. Little attention has been given to the human reactions, at least long-term ones, and the consequences of some of the drastic and large-scale changes are difficult, indeed, to predict. In the symposium, a general concern was felt about this problem but time was not available for adequate exploration of the whole field of the human ecology of deltas.

It is apparent from even superficial observation of the South-East Asian deltas, as well as from one of the studies presented, that frightening population problems already exist in these deltas, and that they are very likely to get worse, rather than better. However, remarkably little concern was manifest in the discussions about the gravity of this matter. It seems clear, however, that all the engineering achievements that can be imagined are only temporary palliatives, and that their effects are doomed to defeat by the geometrical character of this population growth. If man cannot control his biotic potential, his fate is certainly, first to endure increasingly severe regimentation, and, sooner or later, drastic reduction in numbers, most likely by unpleasant means. We can hope that the inherent intelligence of man may find a way out of this situation, but his performance to date does not make one optimistic.

These remarks are generalities. A few of the papers gave specific descriptions, but what the actual patterns are in most of the humid tropical deltas we do not know. In not one of these deltas do we have any approach

to a well-rounded integrated picture of the whole delta ecosystem.

Science, unfortunately, had its infancy and formative period in the north temperate zone—an attenuated, poorly developed part of the world ecosystem. The infinitely more complete, but also more complex, picture of the tropical core area has been neglected and our ideas are warped by our temperate backgrounds. We are only beginning to realize that the temperate zones are merely peripheral to the tropics, not vice versa.

Unfortunately for an ideal unfolding of scientific knowledge, the tropics are a favourable habitat for man—witness his numbers there. In a habitat not at all rigorous, he has succeeded to an appalling degree without even having to try. He is now faced with the problem of having exceeded the peak of his normal population growth, being shielded from the normal crash by the efforts of temperate zone-generated medical science and technology.

We now must contemplate the spectacle of development of delta areas before they are understood, before most of the basic facts and relationships are even known. We build levees, not because we understand the system and know that this is, in the long run, the best thing to do, but because it seems obvious.

If any conclusion can be drawn in the realm of biology it is that we must make a desperate effort to know the plants and animals that live on the humid tropical deltas and their ecological relations before the engineers have placed such knowledge forever beyond our reach. Then we should make this information available to the engineers. They may feed it into their computers from which then may issue a more complete representation of the delta ecosystem. This may provide a valid basis for engineering of a permanent character, rather than the stop-gap solutions now possible.

It has been asked why, since there were so many geographers at the symposium, no mention was made of geography. I can only say that, if my concept of geography, as one of the great integrating sciences, is sound, this symposium and its conclusions are all geography.

Conclusions

F. R. Fosberg

INTRODUCTION

La tâche de dégager les conclusions de ce colloque m'a été confiée; j'en suis flatté et quelque peu effrayé aussi, car je suis peu familiarisé avec les problèmes des deltas et ma compétence est limitée dans la plupart des domaines qui viennent d'être étudiés. Mais je crois qu'il ne faut jamais négliger une occasion d'exposer ses idées quand on a un auditoire à sa disposition. Je collabore au programme de recherches de l'Unesco sur la zone tropicale humide depuis qu'il a été mis sur pied à Kandy (Ceylan), voici huit ans, et je suis aujourd'hui encore président de son comité consultatif. Peut-être est-ce la dernière fois que je prends la parole en cette qualité; aussi vais-je en profiter pour faire quelques remarques qui, si elles semblent n'avoir guère de rapports avec notre colloque, ne sont cependant pas étrangères aux buts que nous cherchons à atteindre.

Tout d'abord, pour tirer de la quantité de communications présentées une idée directrice et des conclusions générales valables, il me paraît utile de dire quelques mots du programme de recherches sur la zone tropicale humide, de sa nature et de sa portée. En premier lieu, je préciserai que nous nous sommes efforcés de le limiter au domaine de la science pure, les applications étant du ressort des institutions compétentes des Nations Unies ainsi que des organismes nationaux; j'ajouterai, en second lieu, que nous avons appliqué à l'étude de l'écosystème tropical humide une méthode largement interdisciplinaire.

Notre propos n'était pas d'entreprendre nous-mêmes des travaux, mais de suggérer des idées et de faire office de catalyseur. Nous nous sommes tout particulièrement préoccupés de recenser les moyens mis à la disposition de la recherche scientifique, d'étudier et de condenser la documentation disponible, puis de présenter cette documentation aux chercheurs intéressés dans le cadre de colloques internationaux, tels que celui-ci. Nous avons surtout cherché à amener des spécialistes de diverses disciplines, ayant une formation et une expérience différentes, à étudier de concert des problèmes ou des ensembles de problèmes qui ne sauraient être résolus s'ils sont envisagés sous l'angle d'une seule discipline. En effet, si complexe est l'écosystème tropical humide que seul l'apport de toutes les disciplines intéressées, avec leur science et leurs méthodes particulières, peut permettre d'en pénétrer la nature. D'où le caractère de ce colloque et la diversité des disciplines qui y sont représentées.

Ce colloque sur les problèmes scientifiques des deltas de la zone tropicale humide avait pour but, à ma connaissance, de dégager les éléments d'information nécessaires au colloque de la CEAEO (ECAFE) sur la défense contre les inondations, la récupération, l'exploitation et la mise en valeur des régions deltaïques.Il s'agissait strictement, à mon avis, de fournir des données scientifiques et écologiques, qui ne font malheureusement pas partie du bagage classique des ingénieurs, mais qui sont essentielles à la bonne réalisation de bon nombre de leurs tâches. Il n'était évidemment pas question pour nous de faire le travail des ingénieurs à leur place : notre mission était, me semble-t-il, de leur faire connaître, en les mettant en garde si nécessaire, les conséquences écologiques possibles et les effets à longue échéance de leurs entreprises.

Or, une fois ce principe posé, l'orientation du colloque semble avoir dévié quelque peu, à tel point que les problèmes techniques et pratiques ont reçu tout autant d'attention que les problèmes purement scientifiques. Si j'en ai été chagriné au début, je n'ai pas tardé à réaliser que je tenais enfin l'occasion longtemps recherchée d'initier les techniciens aux idées et au mode de pensée du biologiste et, plus spécialement, de l'écologiste. Ainsi comprendraient-ils mieux les conséquences lointaines que pouvaient avoir leurs travaux. Peut-être commenceraient-ils à tenir compte des facteurs écologiques et biologiques, comme ils le font des facteurs physiques, géologiques et hydrologiques. Les plans de travaux publics seraient alors conçus de façon plus intelligente : il serait au moins possible de prévoir,

donc d'éviter, certaines conséquences lointaines nuisibles.

C'est pourquoi je me suis finalement réjoui de voir collaborer à ce colloque des ingénieurs et des hydrologues aux côtés de théoriciens de la géomorphologie et de l'hydrologie, de pédologues, de biologistes et même de sociologues, cette dernière catégorie étant peut-être celle dont nous manquons le plus.

On m'a demandé de dégager des conclusions de ce colloque, tâche ingrate s'il en est. En effet, quelle conclusion tirer d'une description, si minutieuse soit-elle, d'un phénomène particulier sinon que ce phénomène existe? Il semble plus logique de grouper mes observations par sujet, plutôt qu'en me référant aux communications présentées, ce qui m'amène obligatoirement à exercer mon jugement personnel. Mais bien plus importantes que chacun de ces sujets sont leurs interrelations, leurs interactions et la portée de ces influences réciproques.

Je commencerai par éliminer les questions qui n'ont guère de rapport avec le thème du colloque. Je mettrai ensuite l'accent sur les sujets d'intérêt purement scientifique plutôt que technique ou agricole. Cet arrangement n'est évidemment pas définitif; les débats feront apparaître toute modification que les participants au colloque désireraient y apporter.

Bien que la répartition par matières qui figure dans le programme définitif ne soit pas parfaite, nous pouvons la reprendre en grande partie ici, à condition de séparer la pédologie de la géomorphologie et de la sédimentation pour en faire une catégorie distincte, et de remplacer le mot sédimentation par le mot géologie, qui est un terme plus général permettant la discussion de plusieurs phénomènes de caractère essentiellement géologique, notamment la subsidence.

Cela nous laisse les matières suivantes : géologie et géomorphologie; pédologie; hydrologie; végétation; biologie; influences humaines.

L'ordre ci-dessus est loin d'être satisfaisant, mais il correspond *grosso modo* à celui dans lequel les débats se sont déroulés.

La plus grave lacune du colloque a été l'absence totale de document d'introduction définissant les caractéristiques générales des deltas, leur distribution géographique et les caractères particuliers de ceux de la zone tropicale humide. Un document de ce genre, rédigé bien avant la date du colloque et distribué à tous ceux qui étaient appelés à y participer, aurait évité bien des erreurs d'interprétation quant au thème de cette réunion, bien des confusions sémantiques et bien des répétitions. Il serait très utile de pouvoir disposer à l'avenir de bibliographies sur les zones deltaïques. C'est une tâche que nous préconisons vivement et dont l'Unesco devrait prendre l'initiative.

GÉOLOGIE ET GÉOMORPHOLOGIE

Il paraît assez artificiel de séparer ces deux domaines comme on le fait couramment en Europe. En effet, si l'érosion et la sédimentation, de même que la subsidence tectonique ou isostatique, sont des processus géologiques, ils ont pour conséquence de modifier la physiographie de la région intéressée.

De tous les phénomènes deltaïques, les mieux connus sont sans doute ceux de caractère superficiel. On peut en effet virtuellement prédire la morphologie d'un delta et ses fluctuations si l'on connaît l'essentiel de ce qui concerne le régime fluvial, la sédimentation, la pédogenèse et la morphologie du littoral, les marées et surtout la pente. Les complications sont le fait de la subsidence — due au compactage ou à la compensation isostatique — et des tempêtes. La complexité est encore accrue par certains facteurs géologiques historiques, notamment les modifications du niveau de la mer et du climat intervenues au pléistocène et à une époque plus récente. Les caractéristiques superficielles des deltas actuels ne semblent pas être, géologiquement, très anciennes.

Le rôle essentiel de la photographie aérienne et des cartes géomorphologiques dynamiques dans l'étude des deltas sur le plan tant de la recherche pure que de la recherche appliquée a été exposé de façon convaincante. Il est manifeste que ces instruments de travail économisent beaucoup de temps et permettent une étude géomorphologique beaucoup plus précise et complète. Pour l'étude du littoral deltaïque, l'emploi simultané de photographies aériennes en couleurs et sur émulsions sensibles aux infrarouges donne d'excellents résultats; aussi est-il recommandé de combiner ces deux procédés pour les levés aériens.

On a également expliqué le mécanisme de genèse d'un delta par la formation de barres dans l'embouchure d'une rivière. Par ailleurs, on a montré que la vitesse des courants, la formation de passes multiples, l'action réciproque de l'eau douce et de l'eau salée, les marées, les vagues, les courants côtiers et même la force de Coriolis sont importants dans le mécanisme d'alluvionnement et, par suite, dans la détermination de la forme même du delta.

La classification des deltas a particulièrement retenu l'attention des participants. La plupart des classifications existantes étaient d'ordre purement descriptif : elles donnaient des groupements logiques, fondés sur une ou plusieurs séries de caractéristiques. Un essai de classification génésique dû à I. V. Samojlov (1956) a servi de base à l'élaboration d'un système génésique détaillé dont la présentation fut le point culminant du colloque. Ses auteurs ont exposé les principes dont cette classification s'inspire, et montré comment une classification véritablement génésique doit tenir compte de tous les éléments dynamiques qui contribuent à la formation d'un delta. En fait il s'agit de bien plus qu'une simple classification : c'est une synthèse des connaissances théoriques et pratiques de géomorphologie qui est presque un véritable tour de force. Elle devrait, pendant longtemps encore, servir de modèle pour le classement génésique des autres phénomènes géomorphologiques.

Il convient de noter qu'on a fort peu parlé du rôle qu'ont pu jouer, dans la genèse et la morphologie actuelle des deltas, les modifications du climat et du niveau de la mer intervenues à partir du pléistocène.

PÉDOLOGIE

La science des sols constitue un domaine assez nettement délimité pour être distinguée de la géomorphologie, encore que, par moments, elle se confonde étroitement avec l'agronomie. Lorsqu'il s'agit de sols cultivés, on aurait intérêt à parler d'édaphologie plutôt que de pédologie.

Les travaux du colloque ont montré que les sols deltaïques sont étroitement liés à la nature du complexe rocheux du bassin hydrographique d'où sont arrachés les sédiments. Tout comme les autres sols tropicaux aérés, les sols deltaïques anciens et bien drainés n'accumulent que peu d'humus; d'où leur faible teneur en éléments nutritifs et le lessivage accentué auquel ils sont soumis. Les terrasses deltaïques anciennes sont peu fertiles et ne se prêtent qu'à des cultures marginales. Les sols mal drainés accusent généralement une teneur élevée en sulfures. Si le plan d'eau s'abaisse, il peut y avoir oxydation des sulfures et formation d'acide sulfurique, ce qui donne les sols très acides dits « cat-clay » ou « kosh » que l'on trouve dans de nombreux deltas. Les sols humides et les sols tourbeux en couche épaisse se rencontrent dans les bassins deltaïques qui sont rarement ou qui ne sont jamais inondés par des eaux limoneuses.

Quant aux sols des deltas plus jeunes ou plus bas, ils sont caractérisés par l'apport annuel de limon arraché au bassin hydrographique par les hautes eaux et répandu à la surface du sol. Ce phénomène tend à donner des sols embryonnaires, mais très fertiles. On n'observe pas d'évolution du profil dans ces sols jeunes.

Les sols sont salins sur le front marin de presque tous les deltas tropicaux, surtout dans les régions où sévissent de fréquentes tempêtes.

HYDROLOGIE

L'eau est l'élément dominant du milieu physique deltaïque. Dans la zone tropicale humide, un autre facteur qui entre en jeu est l'humidité atmosphérique, mais son rôle n'intéresse que peu les hydrologues. L'hydrologie scientifique, d'ailleurs, a tenu relativement peu de place dans les travaux de ce colloque, peut-être du fait que les problèmes d'irrigation et de défense contre les crues, au premier plan des préoccupations, ont déjà été traités par la CEAEO.

On a parlé, mais peut-être pas suffisamment, du rapport qui existe entre l'abondance excessive des eaux de surface et la dénudation de bassins hydrographiques. D'autre part, on a élaboré une formule quantitative exprimant l'augmentation de la salinité de la nappe souterraine, de l'amont à l'aval du delta, par suite de l'évapotranspiration. On a particulièrement fait remarquer la rareté des études qualitatives sur les eaux deltaïques, et des mesures pour combler cette lacune ont été demandées.

L'étroite interdépendance des phénomènes intéressant la nappe souterraine et les eaux de surface a été démontrée et il a été proposé que l'hydrogéologie et l'hydrologie superficielle ne soient plus considérées comme deux disciplines distinctes.

Le rôle des crues, comme facteur de renouvellement de la fertilité des sols, a été souvent mentionné dans les débats, mais les ingénieurs ne paraissent pas y attacher une très grande importance. Leur principal souci semble être non pas d'aider l'homme à s'accommoder de ce phénomène et à en tirer parti, mais de lutter contre les inondations, voire de les supprimer.

Les variations de salinité causées par la mer sont l'un des phénomènes hydrologiques fondamentaux des estuaires et des deltas maritimes. C'est là — sauf lorsque les tempêtes provoquent des modifications catastrophiques — un état normal auquel la végétation naturelle est exceptionnellement bien adaptée. Il est donc étonnant que l'adaptation des activités de l'homme à ce milieu n'ait guère été évoquée au cours de ce colloque. Tout au plus a-t-il été proposé d'étudier la possibilité de cultiver des plantes s'accommodant d'un milieu salin ou, plutôt, de déterminer le degré exact de tolérance à la salinité des cultures actuelles. Pourquoi ne pas étudier aussi la productivité et le rôle écologique de cette zone particulière? Peut-être serait-il plus judicieux d'en tirer parti telle qu'elle est plutôt que d'en modifier l'équilibre. Elle constitue en effet, d'une manière générale, la partie active du delta, celle qui progresse constamment. Quel est le rapport entre cette zone et les ressources maritimes de la région? On l'ignore, et les seules solutions qui viennent actuellement à l'esprit des techniciens sont la construction de digues et l'implantation de cultures qui, cependant, exigent d'une part des capitaux considérables, d'autre part un travail d'entretien perpétuel.

On construit généralement des digues pour se protéger des tempêtes; or on a fait remarquer qu'un écran de mangrove assure une protection tout aussi efficace sans entraîner la moindre dépense.

Les recommandations ci-après ont été formulées à l'intention des organes directeurs de la Décennie hydrologique internationale :

1. Mettre en place un réseau de base permettant de faire des observations hydrologiques normalisées dans toutes les zones deltaïques en cours d'aménagement.
2. Encourager les pays où se posent des problèmes d'aménagement de régions deltaïques à collaborer bénévolement à des programmes communs de mise en valeur.
3. Délimiter des zones types qui serviront à des études détaillées d'hydrologie appliquée.
4. Laisser certaines zones deltaïques témoins dans leur état naturel pour l'évaluation ultérieure des résultats des travaux d'aménagement.

5. Entreprendre l'étude géomorphologique des deltas à partir de cartes géomorphologiques détaillées.
6. Déterminer les différents équilibres dynamiques entre la sédimentation et l'érosion dans les régions deltaïques.

VÉGÉTATION

La végétation naturelle des deltas de la zone tropicale humide est généralement arborée, avec certaines exceptions. Dans la partie salée, la mangrove marécageuse est la formation végétale type. En amont, elle cède la place à des marais d'eau douce et des tourbières où, sur les levées naturelles, poussent des espèces apparentées aux essences forestières à larges feuilles, propres à la région. Dans certaines conditions particulières, par exemple un degré de salinité extrêmement élevé, on peut rencontrer une végétation herbacée ou même une absence totale de végétation. On commence tout juste à avoir une idée des adaptations physiologiques qui permettent aux plantes de survivre dans ce milieu inhabituel et hostile. Des études plus poussées sur la question sont vivement recommandées. Le colloque recommande en particulier à l'Unesco d'encourager les recherches sur la tolérance à la salinité des plantes qui croissent dans les deltas ou qui pourraient s'y acclimater.

Sur le plan géomorphologique, le rôle de la végétation naturelle doit être, semble-t-il, de fixer et de stabiliser les sédiments normalement mobiles, et de contribuer à la sédimentation par un apport de substances organiques.

Quant à la végétation anthropogène, adaptée à d'autres fins, principalement agricoles, elle est beaucoup moins liée à la structure du delta que la végétation naturelle et joue un rôle bien moins efficace dans la fixation des sédiments. Dans les régions deltaïques occupées par l'homme depuis fort longtemps, on ignore d'ailleurs souvent quelle était la végétation originale. Les couches de tourbe et d'autres sédiments stratifiés permettent de penser que des études palynologiques et paléobotaniques pourraient la reconstituer, dans une certaine mesure tout au moins. En attendant, il serait utile de procéder sans plus tarder à des inventaires détaillés de la flore des régions deltaïques tropicales ayant conservé un couvert végétal naturel, celui-ci étant en train de disparaître ou de se modifier avec une rapidité alarmante.

BIOLOGIE

Dans l'étude scientifique des deltas de la zone tropicale humide, la biologie a été considérablement négligée au profit d'autres disciplines telles que la géomorphologie, l'hydrologie et l'agronomie. Pourtant ce domaine est de loin le plus complexe. Ingénieurs et agronomes ont donc effectué des aménagements sans avoir pratiquement la moindre notion de la biologie des deltas. Sans pouvoir affirmer qu'ils ont appauvri ces régions, même comme habitats humains, on peut en tout cas s'effrayer du risque qu'ils ont pris.

Le seul exemple d'étude biologique présentée au colloque et consacrée à un groupe de petits mollusques, les tarets, montre que la plus grande partie de la faune deltaïque n'a même pas encore été identifiée. Si l'on n'établit pas systématiquement des réserves naturelles dans ces régions, la biologie des deltas restera en grande partie ignorée. Ces réserves devraient être situées dans les rares zones deltaïques qui ont échappé à la main de l'homme, et s'étendre de la naissance du delta jusqu'à la mer. Elles devraient être protégées de toute exploitation de façon à pouvoir se prêter plus tard à des études et servir de refuges où une partie au moins de la faune deltaïque peu connue pourrait continuer à vivre. Elles serviraient aussi ultérieurement à l'étude des caractéristiques géomorphologiques des deltas et seraient en même temps des zones témoins pour l'évaluation critique des aménagements effectués ailleurs. Elles permettraient notamment de mesurer à tout moment les augmentations ou diminutions de la productivité selon les différentes formes d'aménagement. Il est à espérer que les pays en voie de développement n'attendront pas aussi longtemps que ceux de l'Occident avant de comprendre que des réserves naturelles sont pour tous les biologistes, quelle que soit leur spécialité, un champ d'études dont ils ne sauraient se passer. C'est dès maintenant, alors qu'il reste encore quelque chose à sauvegarder, qu'il faut établir ces réserves.

Il est recommandé à l'Unesco d'encourager, à l'échelle internationale, l'étude floristique, biologique, microbiologique, pédologique, etc., détaillée de certaines zones types restées à l'état naturel, ainsi que l'étude comparative de l'évolution naturelle d'une zone deltaïque, et de son évolution dans des conditions créées par l'homme.

INFLUENCES HUMAINES

La plupart des grands deltas de la zone tropicale humide sont, partiellement tout au moins, occupés par l'homme depuis de nombreux millénaires. En fait, ils ont été le point de départ de certaines civilisations humaines. Ils sont donc depuis longtemps soumis à l'influence de l'homme, dont certaines interventions, bien que légères, ont eu des conséquences à la fois profondes et d'une portée considérable. Mais l'influence ne s'est pas exercée unilatéralement : le milieu deltaïque a lui aussi fortement marqué de son empreinte les civilisations humaines auxquelles il a donné naissance. Quoi qu'il en soit, les mécanismes déclenchés étaient, jusqu'ici, assez lents pour maintenir un équilibre satisfaisant.

Il n'en est plus de même aujourd'hui, car la technologie moderne a accéléré le rythme de l'évolution au point de compromettre cet équilibre. On s'est peu préoccupé des réactions humaines, tout au moins à

longue échéance; les conséquences de certaines modifications radicales et de grande envergure sont d'ailleurs fort difficiles à prévoir. On a pu constater, au cours du colloque, un sentiment général d'inquiétude à ce sujet, mais le temps qui nous était imparti ne nous a pas permis de faire le tour de l'écologie humaine des deltas.

L'observation même superficielle des deltas du Sud-Est asiatique montre que, comme l'a d'ailleurs mis en lumière une des communications présentées, il s'y pose d'ores et déjà des problèmes démographiques alarmants qui ont toutes chances d'aller en s'aggravant. Mais la gravité de la situation ne paraît guère avoir inquiété les autres participants. Il semble pourtant manifeste que toutes les réalisations techniques qui peuvent être imaginées ne sont que des palliatifs dont les effets sont d'avance voués à l'échec par l'allure de progression géométrique que prend l'accroissement démographique. Si l'homme ne peut contrôler son potentiel biologique, il est immanquablement condamné tout d'abord à une enrégimentation de plus en plus stricte, puis, à plus ou moins longue échéance, à une décroissance démographique radicale qui risque de se faire par des moyens désagréables. Nous pouvons, certes, espérer que l'intelligence dont il a été doué lui permettra de trouver une solution, mais la façon dont il s'est comporté jusqu'ici ne permet guère de se montrer optimiste à cet égard.

Ces remarques ne sont que des généralités. Quelques communications ont donné des descriptions précises, mais nous ignorons encore où en est exactement la situation dans la plupart des deltas de la zone tropicale humide. Pour aucun d'entre eux nous ne pouvons avoir une vue synthétique complète de tout l'écosystème deltaïque.

C'est malheureusement dans la zone tempérée de l'hémisphère nord — partie médiocrement développée de l'écosystème mondial, où les phénomènes sont atténués — que la science est née et a pris forme. Toute la zone tropicale, dont le tableau est infiniment plus complet, mais aussi beaucoup plus complexe, a été négligée, et nos idées sont faussées par notre appartenance au milieu tempéré. Nous commençons tout juste à réaliser que les zones tempérées constituent la périphérie des tropiques et non l'inverse.

Malheureusement pour l'épanouissement idéal des connaissances scientifiques, les tropiques sont un milieu favorable à l'homme, comme en témoignent les statistiques démographiques; cet habitat où les conditions sont loin d'être rigoureuses, il a réussi à le coloniser dans des proportions impressionnantes, sans même avoir eu le moindre effort à faire. Ayant maintenant dépassé l'apogée de sa croissance démographique normale, il n'est protégé de la catastrophe qui devrait s'ensuivre que grâce aux progrès de la médecine et de la technologie accomplis dans la zone tempérée.

Et maintenant il nous faut assister au spectacle de la mise en valeur des régions deltaïques avant même de les avoir comprises, avant même d'en connaître la plupart des faits et des relations élémentaires. Nous construisons des levés, non pas parce que nous comprenons le système et savons que, à longue échéance, c'est la mesure la plus indiquée, mais parce que cela nous paraît évident.

Si l'on peut tirer de ce colloque une conclusion intéressant la biologie, c'est qu'il nous fait faire des tentatives désespérées pour connaître la flore et la faune des deltas de la zone tropicale humide ainsi que leurs relations écologiques avant que les techniciens les aient fait disparaître à jamais. Nous devrons alors communiquer aux techniciens les résultats de nos travaux. Ils en alimenteront leurs ordinateurs, qui pourront alors donner un tableau plus complet de l'écosystème deltaïque et fournir ainsi une base valable à des aménagements de caractère permanent, préférables aux solutions provisoires qui sont les seules possibles actuellement.

D'aucuns ont demandé pourquoi, en dépit de la présence au colloque de nombreux géographes, la géographie n'avait pas été mentionnée une seule fois. A cela, je puis seulement répondre que, si ma façon de concevoir la géographie comme l'une des grandes sciences intégrales est la bonne, ce colloque et ses conclusions sont de la géographie.

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