

SHADOC: a multi-agent model to tackle viability of irrigated systems

Olivier Barreteau^a and François Bousquet^b

^a Cemagref, UR Irrigation, BP 5095, F-34033 Montpellier Cedex, France

E-mail: olivier.barreteau@cemagref.fr

^b CIRAD GREEN, Campus International de Baillarguet, BP 5035, F-34032 Montpellier Cedex, France

E-mail: bousquet@cirad.fr

The viability of irrigated systems in the Senegal River Valley is being brought into question today due to their under-utilization. We assume that their viability depends largely on the way their different components behave and interact. We therefore sought to examine in greater depth today's knowledge of the structure of these systems and activities performed within them. This led to the development of a multi-agent system model, a kind of virtual irrigated system, with a special focus on rules in use for access to credit, water allocation and cropping season assessment as well as organization and coordination of farmers. The purpose of this paper is to show how this kind of tool is relevant to the study of irrigated systems' viability. As an example it is used to examine the influence of existing social networks on the viability of irrigated systems.

Keywords: irrigated system, modeling, multi-agent system, simulation, social networks, coordination

1. Introduction and a few definitions

Irrigation in the Senegal river middle valley developed rapidly from the mid-seventies and especially during the eighties [20]. Today, most schemes developed since then have been abandoned or have undergone one or more efforts at rehabilitation and are underused according to their conception standards [14,15]. This situation raises the question of the viability of these irrigated schemes.

There is a large number of definitions of irrigated systems in the literature [17], each one combining more or less the same components. In this article, we will take the following one: a gravity irrigated system is a network of canals, bringing water from one or several sources to plots for agricultural production by farmers, who may be grouped into producer organizations, and who trade between themselves and with other people not in the system. The whole may or may not be managed by a users' association. It is the place of many interactions between individual and/or collective actors, either direct or *via* the environment.

Viability has also been defined in several ways, by economists [22], systemists [11] and mathematicians [1]. For us, the viability of a system is its capacity

to keep functioning under given initial conditions in a given context. Dealing with the viability of a system is equivalent to checking the existence of a viable path with given initial conditions and constraints.

We therefore need tools to examine the viability of such irrigated systems, tools which allow us to explore paths followed by an irrigated system with certain boundary conditions. This tool must be capable of simulating interactions between people taking into account their perceptions of reality.

2. Field study

2.1. Previous thought framework

Bibliographic studies of water management in irrigated schemes and experience of other renewable resource management studies contributed to the initialization of this work, and to the establishment of an initial thought framework which formed the basis of our field study and of the modeling approach.

Many scientists have highlighted the need for more interdisciplinary research in the field of irrigation management topics [6,9]. From the very beginning of this work, the field study and modeling will therefore have to tackle the different aspects of irrigated system management: hydraulics, economics, social relationships. . .

Several approaches may cope with this need for interdisciplinarity. One consists in the development of several connected partial models, exchanging simulated data, and integrated into a larger, more complex one. Another one focuses on a representation of the irrigated system itself: the important factors to consider in it, the activities undertaken on it, the different relevant time scales, the objects exchanged. With this framework of representation in mind, different types of disciplinary knowledge may be called upon and integrated when needed.

Other work on renewable resources management [16] shows that its analysis and representation often relies upon the study of a “set of rules in use” that Ostrom refers to as institutions. The two former approaches do not properly take these interactions as well as their dynamics into account. We therefore chose to focus on an approach based on enforced rules, both individual and collective, since both exist in irrigated systems, with farmers and farmers’ groups defining an action framework. This approach must also handle interactions between actors, either groups or individuals.

2.2. The schemes

Before dealing with the diversity of rules and interactions encountered in the field, we will first describe the structure of irrigated systems in the Senegal River Valley and the principal activities performed there. We will not make an extensive description of the Senegal valley irrigated systems, for which an abundant literature already exists [3,19].

Figure 1 represents the elements in the structure of different types of irrigated systems in the area and the way they are connected. This is a graphical description

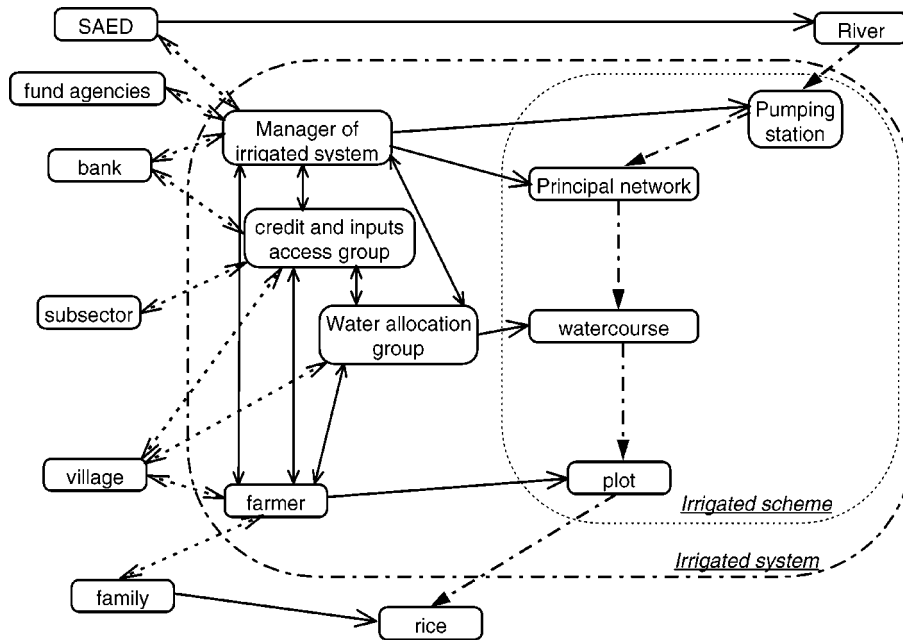


Figure 1. Irrigated system representation.

of elements constituting the irrigated rice-growing systems of the Senegal valley and their interactions with their socio-economic environment. Each component is not an element of every system. This figure shows water first pumped in the river and then running by gravity through the scheme, different actors acting on elements of the scheme. These actors, individuals or groups, are interconnected through membership and service relations. They are also, at their own level, in relation with other actors outside the system. This network of relations at different levels inside and across the boundary is the sign of a complex structure. In addition to this complexity due to their nature, these systems are also the reflection of complex social relationships [5,21]: the local Haalpulaar society is organized on a strict hierarchical basis according to different social ranks, villages and neighborhoods, political tendencies. Age groups may also constitute frameworks of solidarity or sources of conflict. In recent years, a new source of conflict has arisen: some NGOs have claimed exclusive rights to provide services to the people they assist: “if you want me to assist you, do not accept any assistance from another NGO”. This leads to conflicts among the population, with some supporting one NGO and some another. All these relationships generate classes which can also be observed in the field: for example, along a watercourse of 20 plots with farmers all from the same tiny village, one of them claimed not to know who was in charge of another plot.

Complexity also lies in the different activities undertaken in irrigated systems and the sequence of these activities over time. Complexity arises out of the need for some actors to wait until others have performed a particular task before they can take

action. For example, a farmer must wait until the pumps are turned on before he can start work in this plot, but, in some systems, the pumps are not turned on until enough farmers are ready to begin [12].

Moreover, activities related to the scheme are not the only ones to be taken into account: most farmers have several activities [13]. Some have plots in several schemes, others are taxi drivers, others are shopkeepers, while many also have non-profit activities which are not less important: politics or the frequent “problems to tackle” which often take first priority.

2.3. *Alternating field study and modeling*

The description of these spatial and temporal structures was complemented by our field study in order to position this representation with respect to the systems we studied and to acquire information about the diversity of rules and behaviors as well as interactions.

This work is based upon a field study covering 3 years from April 1994 to April 1997 for a total of eighteen months of effective presence in the field. Historically, irrigated systems in the Senegal River Valley follow several different models, depending on the ideas prevailing in the country of the organization conducting the “project” at the time it was performed. As a result, there are several kinds of irrigated systems which differ according to their size, organization and population. We chose 5 different sites following this local diversity in order to cover a large part of the diversity of rules enforced there.

Field study alternated with modeling and simulation: field study leads to hypotheses about the functioning of these systems which are simulated, hence raising new questions for further field study and so on [4]. This cycle was repeated three times, corresponding to three different questions on irrigated systems:

- importance of water management in irrigated system dynamics,
- importance of cropping season preparation and debt circulation in irrigated system dynamics,
- how the cropping seasons are assessed and follow on from each other.

These inquiries provided a lot of information about the way all the different activities are enforced and about the interactions of different actors of the system with each other and with other actors. For the purpose of this article and in accordance with our initial thought framework, the field study then focused on a system dynamics arising out of the perceptions and actions of the population involved in the system, which means a focus on the rules enforced and the way they are put into practice.

The information presented and analyzed therefore focuses on the cohabitation between individual and collective actors in irrigated systems, taking into account the diversity of behaviors: variation of individual behaviors, variation of collective rules, variation of patterns of interaction between farmers. These behaviors will first be described and then implemented in a model capable of dealing with these diversities.

3. Diversity of behaviors and interactions encountered in the field

3.1. Scope of variation of individual rules and behaviors

Several kinds of rules¹ are applied by farmers in irrigated systems: rules for cultivation issues, rules for credit issues, rules for results assessment. . . The first condition that must be satisfied if these rules are to be followed is, of course, that the farmers should want to cultivate for a given cropping season. This depends upon farmers' cultivation objectives which also vary from one farmer to another.

Each rule is applied according to each actor's own mind, depending on each actor's cultivation objective. Farmers may be roughly classified into 4 groups according to the reason why they cultivate their plot, knowing that land is state-owned and attributed to farmers for cultivation.

The first category includes farmers who wish to obtain an income from their plot. They are ready to invest a large amount of money through pesticides and fertilizers as well as a large amount of work. For these farmers, the acquisition of these two resources is not really a problem: they often have several plots and may rely on several people to help them on the plot (sons, relatives or descendants of slaves). Consequently, people are frequently present on their plot, monitoring the water level, the state of the crops, presence of weeds. . . And they generally have access to appropriate farm inputs when the plot needs them.

The second category includes farmers who want their plot to provide them with the food their family needs. They often only have this plot to rely on. They are not willing to spend as much money as farmers of the previous category because of the risk involved in investing money on a single plot. Nor will they ensure a frequent presence of someone on their plot: they have other activities to do, including money-making activities. It is sometimes more difficult for them to reimburse their debts and to obtain farm inputs at the right time. They may have to resort to family members outside the areas.

The third category includes farmers who simply want to keep the plot. They do not expect it will bring them anything, they just make sure that it does not cost them too much. The behavior resulting from this attitude consists in a low level of investments and an infrequent and irregular presence on the plot. Activity on the plot never takes priority but since they do not want to lose money on their plot, these farmers may bend certain collective rules to their advantage.

The fourth category includes young jobless men whose family refuse to allow them to go to St. Louis, the nearest big city 200 km away, or Dakar, the capital, to find a job. Therefore they work for a season on a plot a relative lends them, waiting for a hypothetical new building site in the area which might employ them. Moreover, they are not as motivated by what is happening on the plot as other farmers are. Investments depend on other family members.

¹ In this paper, a "rule" is something imposed or adopted as a way of behavior. It may be either individual or collective.

These different cultivation objectives give a first indication of the scope of variation of individual behaviors. In fact, farmers enforce many more rules in their daily practice of rice cultivation: choice of a rice variety, use of farm inputs, destination of produce, arrangements with other farmers, compliance with collective rules, lending and borrowing of money. . . All these rules can be applied in a wide variety of ways.

As regards borrowing, for example, when a farmer needs money for the cropping season, he requests a loan from the source where he thinks he has the best chance of success. The first source of credit in this case is often the GIE of which he is member (GIE is the French acronym for economic interest grouping, which is a structure authorized to obtain loans from the national agricultural bank). But the farmer may face one of two obstacles: the GIE may not have money to lend, or the farmer may not be in compliance with the credit attribution rules. Farmers have other possibilities for obtaining credit such as community funds, merchants, other farmers and relatives. Requests for loans from other individuals will depend upon their social relation with the borrower, the chances that the borrower's request will be accepted or his willingness to become indebted to certain people. The amount requested is also quite variable: some will borrow as long as they need credit, others will do it as long as they think they will be able to repay. When it is time to repay the loan, behaviors again vary with respect to reimbursement priorities and willingness to pay. In individual lending to others, the rule enforced at present is mostly governed by social status. If the guy who is asking you is of a lower class you cannot refuse to lend to him. Here the only variations concern the amount you lend: from a single symbolic note to the full amount he is asking for.

The way farmers evaluate their practice on their plot also varies from one farmer to another, leading to changes in the practiced sets of rules. These changes are effected in two stages and must respect certain conditions. The first step is evaluation of rules in use. Evaluation criteria vary from one farmer to another: debt level, output. . . The second stage, a rule change, is implemented if this evaluation is not satisfying. A rule change is often an imitation of other farmers who either seem to be succeeding with their practice or who impose certain types of behaviors because of the externalities they impose upon other farmers. Only a few will try new practices. Whatever the results of the evaluation, the new rules must conform to some fundamental rules of society such as avoidance of conflicts or social solidarity.

All these variations cannot be reduced down to a single one, such as the farmer's objective in cultivating his plot: one farmer may have a land-based goal and prefer to sell his rice himself while another farmer with a land-based goal will prefer to let his group sell his rice and reclaim the money afterwards. The mode of application may depend on several criteria such as family composition, social status of the family head. . . Since our purpose is to explore the scope of rules enforced in an irrigated scheme we did not investigate further where these differences come from.

3.2. *Scope of variation of collective rules*

The collective rules enforced are numerous and variable, in declaration as well as in fact. Water allocation among farmers along a watercourse may be based on a water rotation (the first farmer takes water as long he needs it and then leaves the whole flow to the following one) or a system of free access (any farmer may take water when he wants to) or a combination of these two rules (for example a water rotation at the beginning of the cropping season and free access when each plot has had its first watering). At the scheme level, water management depends on the group in charge of pumps. This affects water availability through pump start-up and shut-down rules and through the daily duration of pumping.

As regards financial aspects, the most relevant collective rules encountered are those dealing with credit distribution, water fees determination and sanctions if credits are not reimbursed or fees not paid. GIEs give credit to their members according to different conditions. Not all GIEs lend as soon as funds are available. Some check if the borrower is not already indebted or if the running credits of members as a whole are not too large. Finally, some estimate if the borrower will be able to reimburse the credit whatever his level of debt. Water fees are fixed in one of two ways: either a fixed sum corresponding to the area irrigated or a share of real pumping and principal network maintenance costs proportional to the borrower's irrigated area at the end of the cropping season. When water fees are not paid in full, the group in charge of its collection may react in several different ways: no reaction as long as there is enough money overall to operate the scheme, a threatened prohibition of access to water, withdrawal of the plot by the group which then attributes it to another farmer able to pay, shutting of all watercourses for which overall fee payments have not been paid, negotiation of a schedule of repayments. In fact, radical solutions such as withdrawal of the plot are rarely enforced because, as a leading farmer said, "I will not shut off my own watercourse", and most leaders are as indebted as other farmers, if not more.

The evolution of collective rules follows the same pattern as individual rules. Evaluation is generally made by a few leading farmers, sometimes according to the level of satisfaction of the majority of farmers.

3.3. *Nature of interactions between farmers*

Our initial hypotheses also called for a special focus on interactions between farmers in irrigated systems. The collective rules described above define a first set of interactions between farmers. These interactions are mediated by collective rules which may be used as a reference in the event of conflict and which are sometimes enforced by a third party. This third party may be the group leader when an active leader exists, which is not always the case, especially for water allocation groups.

Interactions between farmers are also mediated through the environment: water availability downstream if upstream farmers take water, participation in maintenance works. Institutions such as water allocation groups to facilitate the coordination required to handle these interactions do not always exist. In some irrigated schemes

there are no institutions designed to coordinate water allocation. In those cases some farmers along a watercourse do not know other farmers whose plots are along the same watercourse.

There are also direct interactions between farmers. They may concern, for example, exchange of services or of information about one farmer's plot in particular or the current state of the scheme. Collective work on plots sometimes takes place for certain activities such as planting (in some systems planting is coordinated by a group managing a watercourse or the principal network) or harvesting. The exchange may also have one foot outside the irrigated system: a farmer who knows something about mechanics will repair the motorcycle of another who will then work on the other's plot in exchange. This balance of exchange, one service against another, is not always the case. There are also interactions involving farmers working on others' plots apparently without any service in return: a descendant of a captive will work on the plot of the descendant of the former master of his forefathers, sometimes without the latter actually asking him to do so. Actually all these interactions often originate outside the irrigated system but go through it. This is notably the case for the various friendship networks mentioned earlier.

4. Modeling of this system: SHADOC

The system described above is a complex system involving many rules with several modes of application possible for each of them and numerous interactions at different levels. This description has been used to make a model, SHADOC (French acronym for hydro-agricultural simulator describing organization and coordination modes), along with the acquisition of information in the field.

4.1. Modeling assumptions

This model is based upon certain assumptions. Basically we assume that irrigated systems may be represented as a place of acquisition and distribution of two resources: water and credit. After a first modeling step with water alone playing the first role, it appeared that exchanges between farmers have a more important influence on the number of undesired dried-out plots than collective water allocation rules [2]. Since these exchanges most often take place during preparation of the cropping season when the farmers' first activity is credit related, we have retained this assumption.

This first choice limits the scope of other possible assumptions, in particular for the different kinds of groups allowed into the model. Simulated society is assumed to be structured with only three types of irrigated system related groups – credit management, watercourse and principal network and pumping station – one friendship network, the archetype of all existing networks, and a four-level social categorization.

These assumptions have a number of consequences. Concerning the physical model, questions about maintenance are not dealt with, hence limiting the meaningfulness of simulations over long time periods. It is therefore useful to limit the number of

possible cropping seasons for a simulation. The water model is also quite simple due to the one-day time step of the model. This time step was chosen because it focuses on the application of rule enforcement in the system which is most often once a day. The hydraulic model chosen is therefore a volume balance model computed for each plot:

$$WL_{t+1} = WL_t - ETR + Irr \quad (WL_t \text{ being water level at } t).$$

Agronomic aspects are also drastically simplified. The crop management sequence is reduced to the actions concerning irrigation alone and the choice of and amount of farm inputs. The set of technical references is assumed to be of the same quality and followed with the same application for irrigation as for other components of the crop management sequence. Therefore yields are simulated in three steps: at the beginning of the cropping season a potential yield is determined according to investment amount in inputs and variety of rice chosen, then along the season this potential yield is decreased at each moisture stress event according to FAO equation² [7], at the end of the season the resultant potential yield is multiplied by a random factor.

As regards economic aspects, focus on credit means that money is represented as the only input in the plot and the only output. It assumes that there are no problems of rice marketing or farm input availability. This is not exactly the case in the Senegal river valley, but up until two years ago, repayment with rice was the common rule and is still very frequent. When credit is provided by groups, it is often directly in the form of farm inputs. We will therefore maintain this limitation.

4.2. Representation of irrigated systems in the Senegal River Valley

In all of this subsection, the subject is the model, and thus computer agents, objects and attributes rather than farmers, plots and rules and criteria. This is not always taken into account for the flow of the text but must be kept in mind and understood as if it were always specified.

The set of assumptions above leads to a model of irrigated systems. This model comprises two parts: a model of the scheme on the one hand with its own structure and its own dynamics, a model of social organization on the other, also with its own dynamics and its own structure. Links between these two parts lie in the management and the farming of the first by the second. This model, which takes the form of a multi-agent system [8] was produced using the object-oriented method and is implemented in SmallTalk language under VisualWorks[®] environment.

4.2.1. Simulated scheme model

The main classes constituting the scheme model are described using the OMT method [18] in figure 2. Regarding the number of instances, for the scheme model currently used, there are one pump station, one reach, symbolic of the whole principal

² θ being water content during the moisture stress event, if $0.33 < \theta < 0.75$, potential yield is multiplied by $0.8 \cdot (3\theta - 1)$. If $\theta \leq 0.33$, potential yield becomes null.

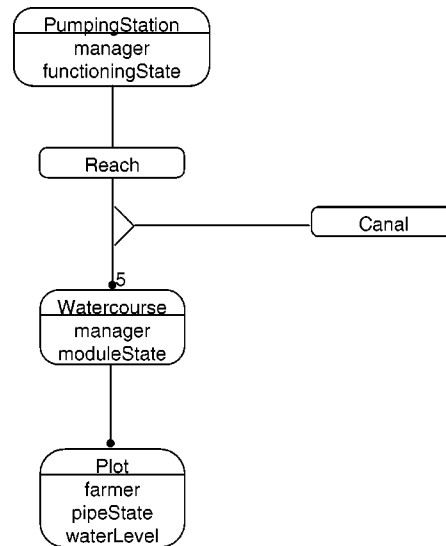


Figure 2. Scheme representation structure. The Reach and Watercourse class both inherit from the Canal class. Each PumpingStation class instance is in relation with only one instance of the Reach class (and vice/versa). Each Reach class instance is in relation with exactly five instances of the Watercourse class, which are each in relation with exactly one instance of the Reach class. Each instance of the Watercourse class is in relation with many plot instances, which are in relation with exactly one Watercourse class instance.

network, to which five watercourses are connected, each watercourse being supplied by a constant flow offtake regulator. A variable number of plots are located along each watercourse.

The PumpStation class instance acquires a quantity of water according to its functioning state and to the choice of operating rule made by the agent referenced to by its attribute manager. Pumped water flows, up to the limit of its capacity attribute, through the Reach class instance which distributes water to opened Watercourse instances from upstream to downstream according to the size of their module and water availability. Each Watercourse instance distributes water received to Plot instances along itself with pipeState attribute #open. If several Plot instances have their pipeState attribute #open, the most upstream one receives roughly half of the flow, the others sharing among themselves the residual flow in the same manner, giving an advantage to upstream plots along the way. At each time step, the waterLevel attribute of each Plot instance diminishes according to a global and constant simulation parameter representing evapotranspiration and infiltration. This drying is halved when the waterLevel attribute is negative, the soil water reserve being fixed at 15 cm for each Plot instance.

4.2.2. Simulated society model

The different classes constituting the simulated society, to which the simulated scheme is attributed, are described in figure 3.

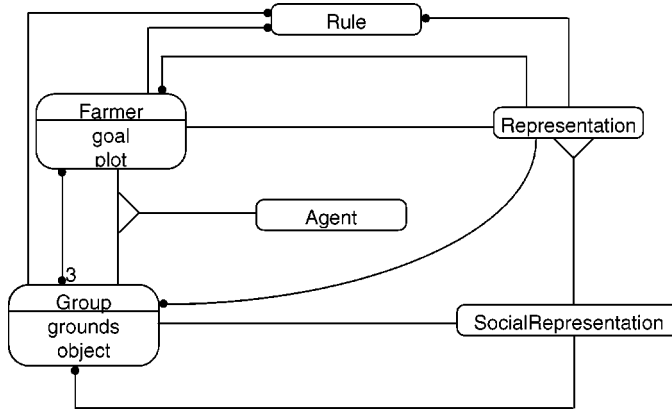


Figure 3. Society representation structure. The Farmer and Group classes both inherit from the Agent class. Each Farmer class instance is in relation with exactly three instances of the Group class, one instance of the Representation class (which inherits from the SocialRepresentation class) and several Rule class instances. Each Group class instance is in relation with several Farmer class instances, several Rule class instances and exactly one SocialRepresentation class instance. Each Representation class instance is in relation with several Rule class instances, several Farmer class instances and several Group class instances.

Each Plot instance is attributed to one Farmer instance, having itself only one plot. Each farmer agent belongs to three different kinds of group agent:

- One whose grounds attribute is #waterAllocation among farmer agents with their plot attribute along the same Watercourse instance. Each Watercourse instance is hence managed by such a group agent.
- One whose grounds attribute is #pumpStation management. This group agent includes all farmer agents of the scheme represented.
- One whose grounds attribute is #creditAccess for its members. The composition of these group agents is *a priori* different to the composition of #waterAllocation group agents.

Each agent acts according to a set of rules local to him, whose format depends on its class and its grounds in the case of a class Group. Each farmer agent acts also according to his own goal attribute from the set {#production, #food, #land, #waitingBetter} which takes up the categories described in section 3.1. Each agent has also its own point of view about the state of the system and especially its potential relations with other agents. This representation contains, for a farmer agent especially, his knowledge of the water level on his plot, his friendship network constituted by other farmer agents with which he will be willing to cooperate through exchange of information or services and, finally, assumed rules enforced by agents with which he is in relation.

Table 1 sums up some of the classes used in this model and the number of each one. These are not the only ones. The Rule and Communication classes are not in this table because their number varies throughout the simulation process, though they are also very important in the model.

Table 1
Number of agents and objects.

Class	Number of instances
PumpStation	1
Reach	1
Watercourse	5
Plot	$30 \leq N_p \leq 100$
Farmer	N_p
Group	$7 \leq N_g \leq 11$
(Social)Representation	$N_g + N_p$

4.2.3. Dynamics of the model

The dynamics of the multi-agent system is represented in the following figures with Colored Petri Nets [10]. Figure 4 represents the dynamics of the whole cropping season. At the beginning of the cropping season each farmer is in a waiting stage and randomly enters the credit search stage. Each one who succeeds in obtaining credit and permission to irrigate enters the irrigation stage, others give up. Those who are in the irrigation stage try to irrigate their plot in order to sow. Those who fail for too long give up. Others cultivate the plot and then harvest. At the end of the cropping season, each farmer assesses his results and is ready to play again. It is now useful to describe the dynamics of the three stages.

The credit search stage, described in figure 5, comprises three steps:

- evaluation of amount needed to be authorized to sow rice in his plot and be able to buy farm inputs for it,
- search for corresponding credit,
- request for authorization to get irrigation water.

The first step is done in one of two ways depending on the farmer's access to group information. Either he may get information from the pumping group and ask it how much he has to reimburse to be authorized to sow rice, or he may not, in which case he estimates this condition from its representation of the group's corresponding rule.

In the second step, each farmer asks for credit from agents, group or farmers, he thinks will be the most ready to lend him money. He does one request each time step as long as he has not found enough.

Finally when the needed amount is found he asks the pumping group for authorization. If he does not comply with collective rule for access to irrigation water, the group denies him authorization and then he goes back to the first step, otherwise he switches to irrigation stage.

Plot sowing divides the irrigation stage into two steps for each farmer. The whole stage is described by figure 6.

Initially, the purpose is to get information about the start-up of the pump station, either from a farmer in the friendship network or from the pumping grounds group. When he gets this information, he updates his representation of pump station func-

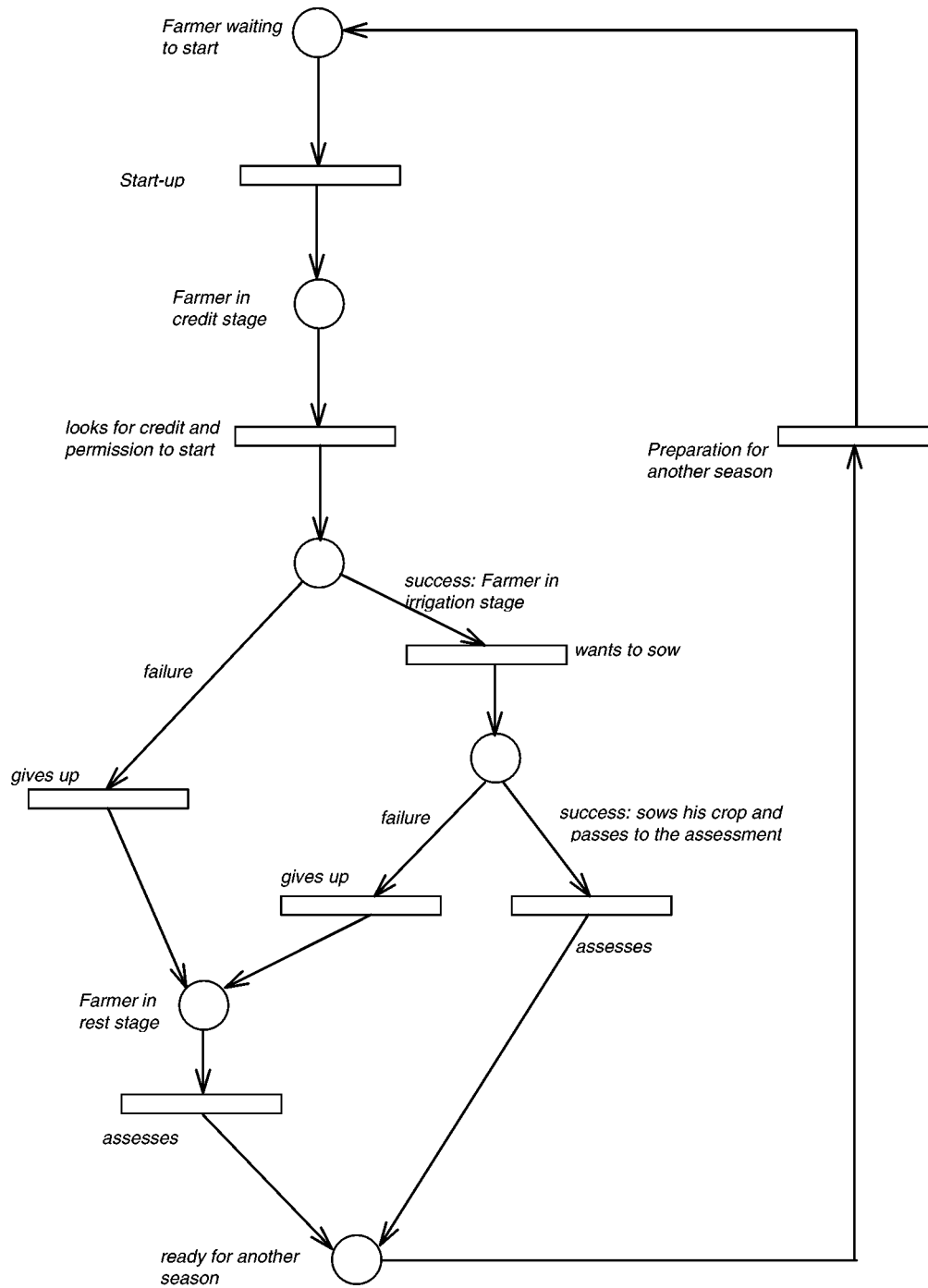


Figure 4. Representation of cropping season development.

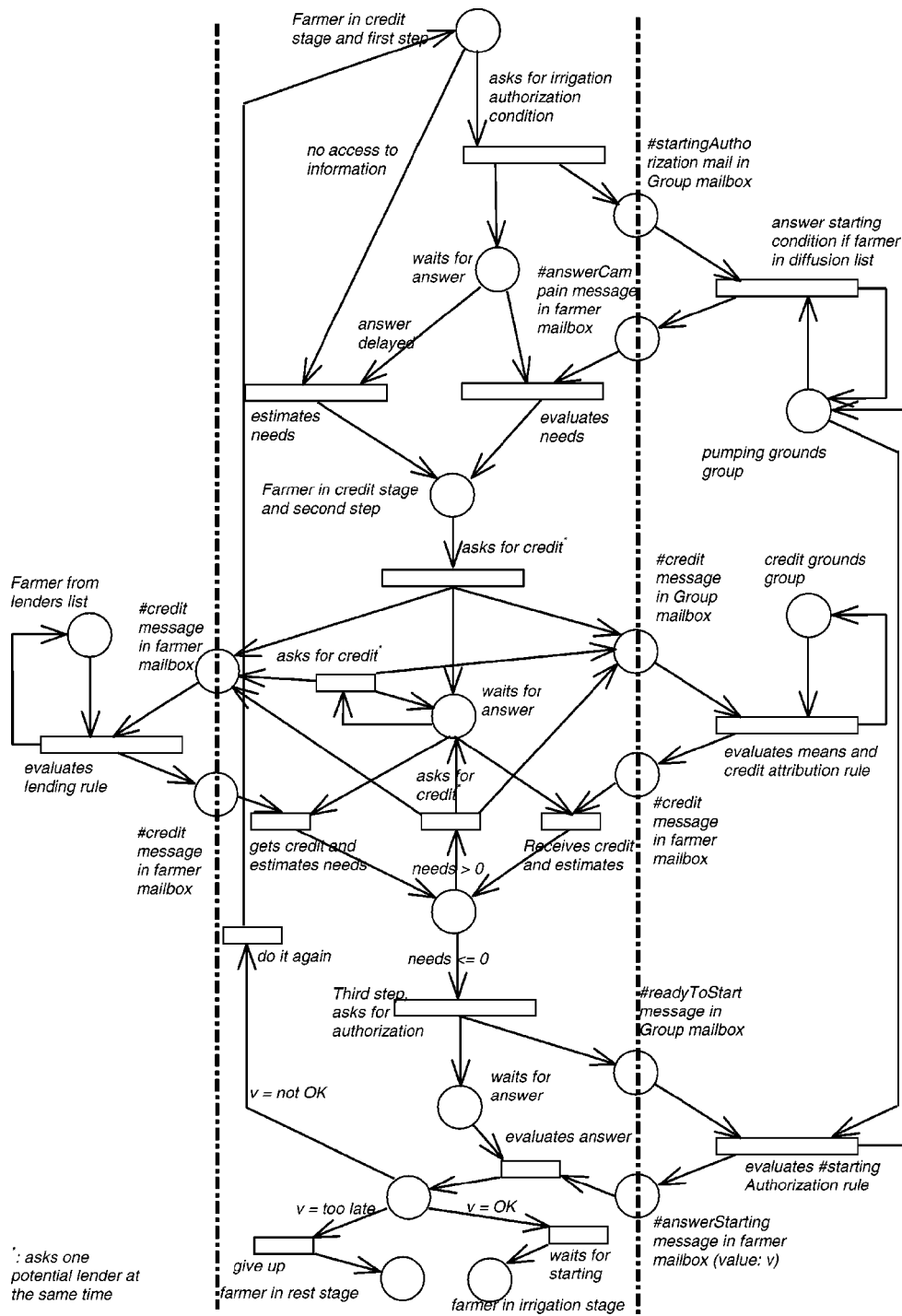


Figure 5. Credit stage representation.

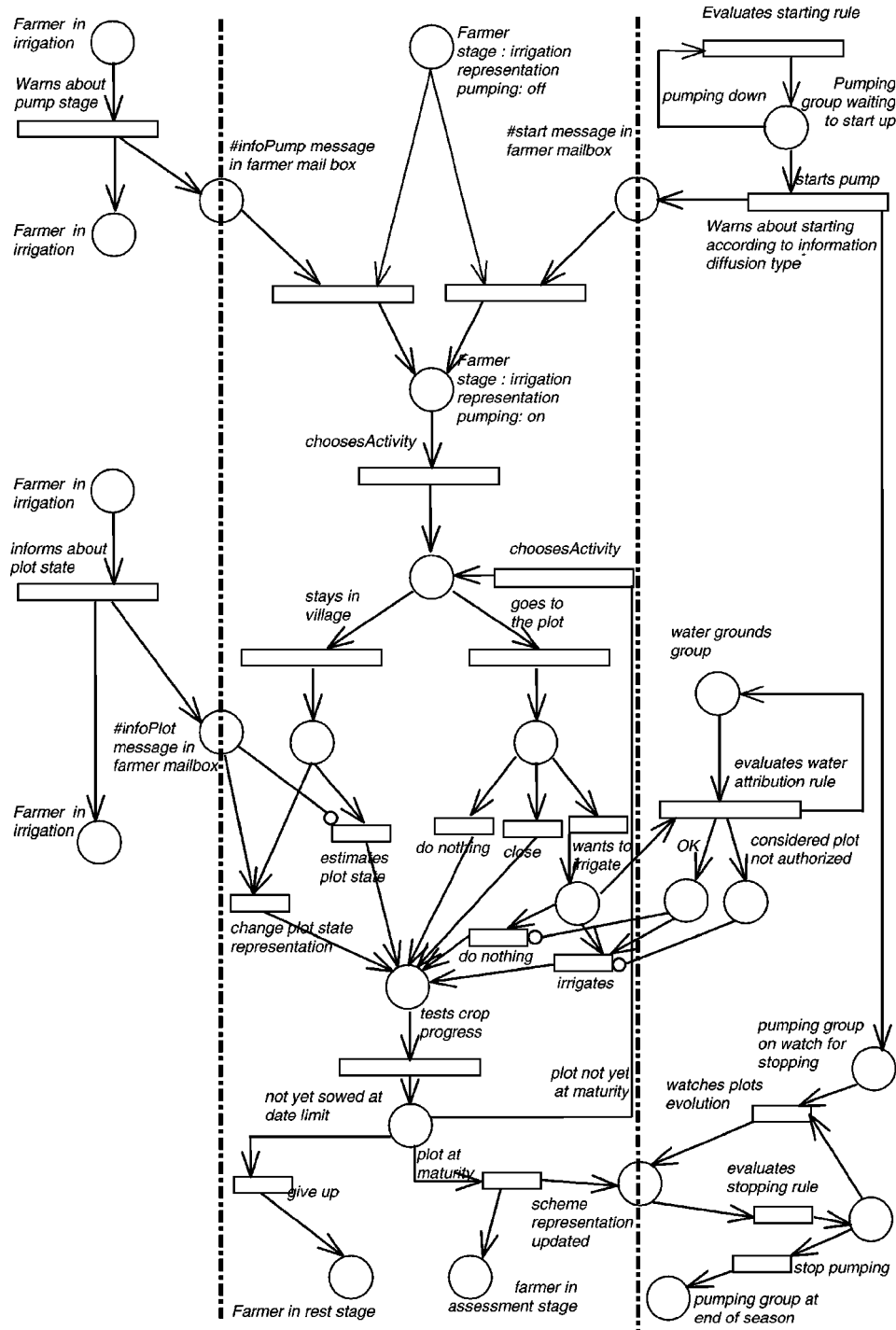


Figure 6. Representation of irrigation stage.

tioning state and seeks for sowing his plot. While sowing, he chooses according to his representation of end of season collective rule the longest cycle rice variety he can crop among three possibilities: short, medium or long.

Then, at each time step, the farmer has to choose to go or not to go to the field, depending on his goal and his representation of the plot water level and pipe state, pump station functioning state and the possibility of getting water. This choice is made at each time step and for each farmer through the comparison of a random number to a probability threshold which depends on farmer's goal and representation.

When he goes to the plot, he checks the water level. If it is under a minimum reference level and the pipe is closed, he wishes to irrigate, whereas if it is above a maximum reference level and the pipe is open, he closes it. If he wishes to irrigate, he opens his pipe if watercourse management rule authorizes him to do so. Otherwise he asks the farmer who is authorized to irrigate to let him irrigate at the same time, if this second farmer is in his friendship network. If this is the case and if the first farmer's plot does not need too much water, he gets authorization. While on the plot, he may see friends' dried plots along the same watercourse as his plot, in which case he sends them a message about their plot water level. If he does not go on his plot, he updates his representation of his plot according to information he may receive or, if he does not receive information, according to his experience. If he has not been able to irrigate late in the cropping season, he gives up.

At the same time, pump station management group updates at each time step its representation of irrigated scheme state. According to the fulfillment of its rule of ending cropping season, it uses its representation to stop pump station. Then each agent switches to third stage.

Figure 7 describes the assessment stage. When the cropping season comes to the end, whether or not they have taken part in it, each agent assesses what has happened in order to draw conclusions for following cropping seasons. Each one evaluates his satisfaction criterion. If satisfied he changes nothing in his rules. If not satisfied, he may change his set of rules according to one of the following methods:

- changes nothing,
- imitates the agent of his "imitation group" with better score for his own criterion,
- selects agents of his "imitation group" who would have satisfied his criterion and imitates the one with the behavior nearest to his,
- imitates the best for a short while then reverts to his former behavior.

For each farmer, the "imitation group" is the group of farmers he may collect information from (i.e., in this version of model, his friendship network) and which he thinks it is worthwhile to compare himself to. This may take a number of forms for each farmer: the whole friendship network, the intersection of the friendship network with the water allocation group, the intersection of the friendship network with the credit access group, the intersection of friendship network and water allocation group and credit access group. For each group, the "imitation group" is the set of all other groups

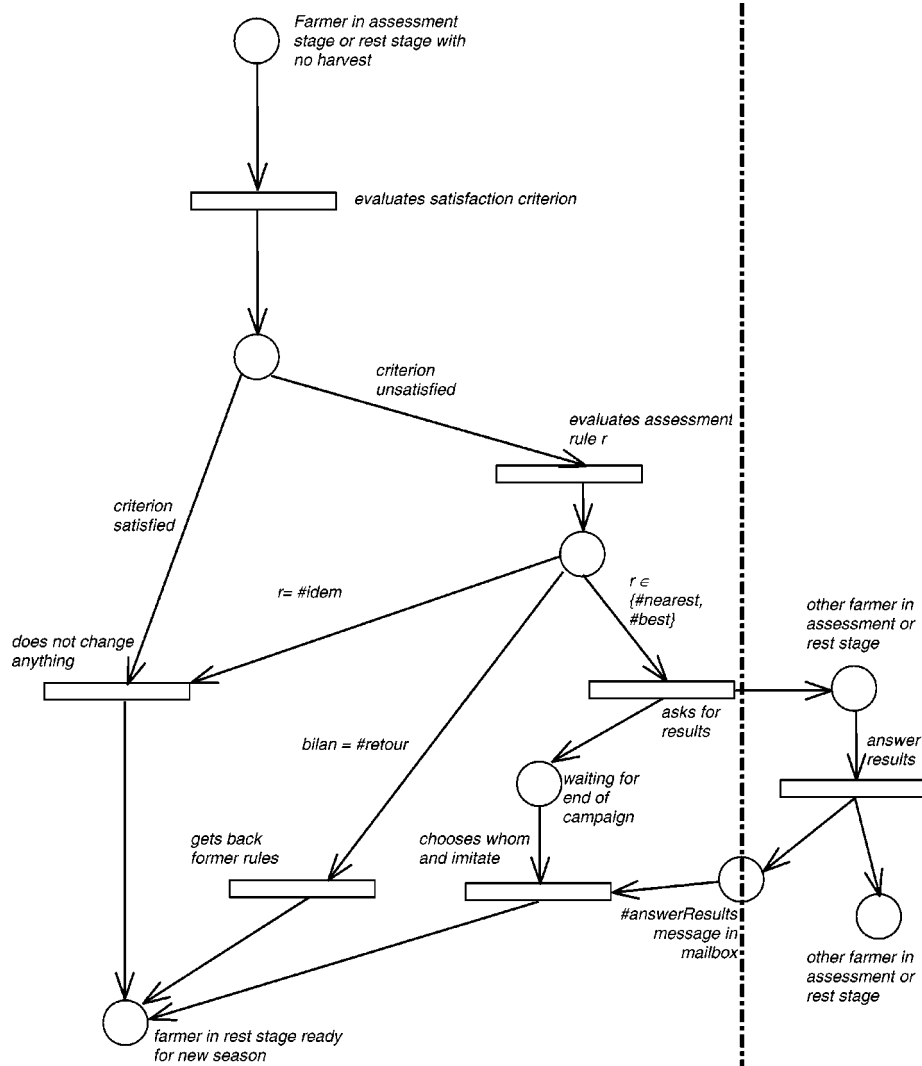


Figure 7. Representation of assessment stage.

with same grounds. In imitating another agent, a farmer adopts the whole set of rules of this agent for himself. An imitation consists for an agent in switching its set of rules to the one of the other agent it imitates.

4.3. Possibilities for further modifications

This model described above has been designed from a particular field research project and a specific question. Even though a quite large range of cases has been taken in account, it may be considered at a first glance as too specific for use in another context.

But the framework of representation can actually be used in other contexts. The various classes implemented regroup the most pertinent items of most gravity irrigated systems: Farmer, Group, Plot, Canal, Pump, Rule, Communication, Credit. Only a few particular instances may change from one context to another: type of rules, mode of application of each type of rule, types of communications, grounds of groups. The elements are in place provided that relevant information is supplied.

5. Possible uses of this model

5.1. As a research and experimentation tool

This model was first designed as a tool for simulating scenarios of collective rules and individual behaviors. The model user may choose among different modes of application for each collective rule or individual behavior as well as the structure of interactions included in the model. He may also choose among several physical parameters such as infiltration and size of each watercourse. The first step in using this model is hence to choose a scenario, which may be formalized as a triplet $\langle C, I, E \rangle$, C being a set of initial collective rules, I being a set of initial individual behaviors and E a set of relations to the environment. A scenario synthesizes hypotheses of rules enforced in an irrigated system. Hence the model allows to study the evolution of an irrigated system in different frames of rules hypotheses. The choice of scenarios can be made either through the model interface shown in figure 8 or through files of parameters.

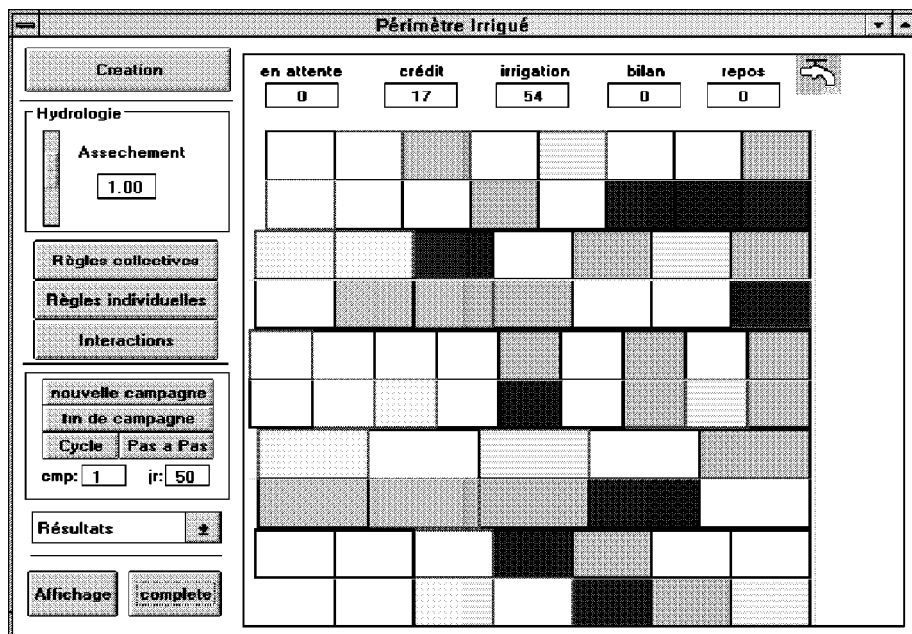


Figure 8. Model interface.

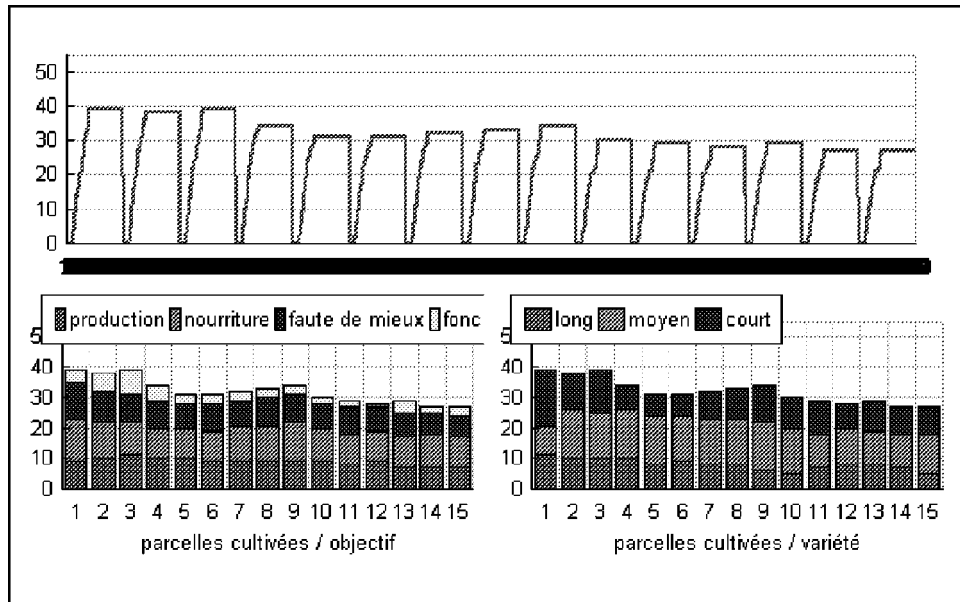


Figure 9. Number of plots irrigated through time as an output of the model. Here is an example of output for a viable simulation. Top figure gives number of plots irrigated each day along the fifteen cropping seasons of this simulation, while both others give the number of plots cultivated for each cropping season, the left one according to the farmer agent's goal, the right one according to the chosen rice variety.

Then comes the time of simulation. The longest ones may last up to one hour on a PC with a first generation Pentium® processor. Several indicators are available throughout a simulation, some at a day time step, others at a cropping season time step. They may be classified into three groups: viability indicators, factors whose effect on viability is represented, factors possibly influencing viability but whose effect is not directly taken into account. Viability indicators deal with the evolution of the number of plots cultivated over time, as shown in figure 9. The second group of indicators is the largest, it regroups the evolution of the number of plots in a situation of moisture stress, the evolution of farmer satisfaction, payment of water fees, farmers' wealth, water consumption. Indicators about the evolution of the number and themes of communications and about the population of rules used may also be considered in that class at a second order level. Both are assumed to direct the evolution of other factors in this category. Finally, the third group comprises only one indicator for the moment: respect for a social solidarity rule.

Section 4.1 lists the different assumptions in the model and some of their consequences. The most important consequence is the nonsense of using a scenario simulation result by itself. The model uses several randomly generated values and some imposed thresholds. A simulation for one scenario must be therefore repeated several times and interpreted mostly by comparison with simulations of other scenarios, possibly by itself but only for tendencies it may show.

For the moment, this model has only been used as a research tool to explore the consequences of some hypotheses on behavior in an irrigated system [4]. The less important effect of the water allocation rule mentioned earlier is one result of these research uses. But researchers may not be the only people interested in such a virtual irrigated system. Irrigation specialists may use it to simulate the effect of a design choice (a set of collective rules) with varying uncontrolled parameters (for example some individual behaviors) in order to observe the scope of variation of some expected results and possibly to enforce other design methods to limit this variation.

5.2. Example: influence of social networks on the viability of irrigated schemes

The model presented above is the result of an evolution of an initial, simpler, version which led to a more subtle representation of the role of social networks in the evolution of irrigated systems. It is interesting now to perform further simulations to examine the influence of social networks on the viability of irrigated schemes.

A first set of 100 random scenarios were used through 5 series of 20 simulations which proved that these random scenarios could be ranged in three classes according to their viability defined upon the rate of viable simulations among 20: 0 or 1 viable simulation, 2 to 9 viable simulations, 10 or more simulations are viable. A simulation is considered to be viable if it lasts more than four cropping seasons with at least one cropping season after the fifth one practiced by more than 20% of farmer agents. The two first classes got a number of roughly 40% each, and the third one of 20%. 5 scenarios were then chosen from among them such that there are 2 in class 1 (named scenarios A and B) and 2 (scenarios C and D) and 1 in class 3 (scenario E).

In the following experiments each of these 5 scenarios keeps all its parameters constant except those possibly implicated in the influence of social networks on the irrigated scheme.

These varying parameters are as follows:

- “Homogeneity”. If this parameter has a “true” value, #creditAccess group agents and friendship networks have the same composition as #waterAllocation group agents. Otherwise these group agents are *a priori* independent.
- Number of friendship networks.
- Vector with percentage of farmer agents for each mode of imitation set constitution.

This gives a set of 95 scenarios defined as in table 2.

In this table, imitation sets are described by four component vectors $(\alpha, \beta, \gamma, \delta)$, with:

- α : rate of farmers whose imitation set is their friendship network,
- β : rate of farmers whose imitation set is the intersection of their friendship network with their water allocation group,
- γ : rate of farmers whose imitation set is the intersection of their friendship network with their credit group,

Table 2
Modifications of parameters to test the consequences of friendship networks for irrigated systems viability.

Initial scenarios	Homogeneity	Number of friendship networks	Imitation set
A, B, C, D, E	true	5	$v1, v2, v5, v6$
A, B, C, D, E	false	1, 3, 5	$v1, v2, v3, v4, v5$

Table 3
Number of simulations in each viability class for each group of scenarios.

Initial scenario	Initial class	Number in class 1	Number in class 2	Number in class 3
A	1	19	0	0
B	1	19	0	0
C	2	3	16	0
D	2	0	14	5
E	3	0	2	17

- δ : rate of farmers whose imitation set is the intersection of their friendship network with their water allocation group and their credit group.

Vectors simulated are the following ones:

- $v1 = (100, 0, 0, 0)$,
- $v2 = (0, 100, 0, 0)$,
- $v3 = (0, 0, 100, 0)$,
- $v4 = (0, 0, 0, 100)$,
- $v5 = (25, 25, 25, 25)$,
- $v6 = (50, 50, 0, 0)$.

Note that with a “true” homogeneity value, the number of friendship groups is automatically 5 and the three last components of vectors describing imitation sets are equivalent.

Simulations were only observed through the number of cropping seasons performed and the evolution of number of plots cultivated for each one. A first result concerns the scope of the effect of these changes on the initial scenarios they were built on. As shown in table 3, for each initial scenario, nearly each scenario inferred from is in the same viability class, which is the initial scenario one. For each scenario, simulations were repeated 20 times, except the third one which had low frequencies of viable simulations for which there were 50 repetitions.

This shows that the scope of variation of results is not very wide around the initial value. Social networks alone cannot be considered to explain the viability class of a scenario. For initial scenarios C and D, the few changes observed are due to the initial scenario located near the boundary of the class.

Table 4
Frequencies of viable simulations according to number of friendship groups.

Number of groups	Initial scenario C (%)	Initial scenario D (%)	Initial scenario E (%)
5	2.8	45	69
3	3.6	47	77
1	4.8	53	81

Table 5
Frequencies of viable simulations for each imitation set value.

Imitation set value	Initial scenario C	Initial scenario D	Initial scenario E
(100, 0, 0, 0)	3	41.25	80
(0, 100, 0, 0)	8	53.75	71.25
(0, 0, 100, 0)	4.5	42.5	67.5
(0, 0, 0, 100)	6.5	43.75	67.5
(25, 25, 25, 25)	1.5	51.25	66.25

But there may be a local effect of these social networks. Table 4 compares mean frequencies of viable simulations for each number of friendship groups with a “false” homogeneity value and a varying value of imitation sets.

This shows that even if social networks cannot be used to explain the viability of some scenarios, the number of friendship networks still has a minor effect, which is the same as observed in the first model version: the less divided the population, the more viable the irrigated system. That means, unsurprisingly, that for one scenario, the reduction in the number of friendship networks raises the probability of viability of a simulation, in other words, the more people get along the higher the probability of viability of a simulation for a given scenario.

As regards the effect of the imitation set, table 5 compares mean frequencies of viable simulations for each imitation set value with other parameters varying.

A population of farmers with imitation sets limited to farmers along the same watercourse seems here to be another factor raising the probability of viability for a simulation of a given scenario, since it ranks twice first and once second. This calls for a closer study of the effect of rule changes and for a return to the field to gain a better knowledge of the way these imitation groups are constituted.

Finally, the homogeneity parameter seems to have no effect according to table 6, which compares mean frequencies of viable simulations for each homogeneity value, the number of friendship groups being fixed at 5 and imitation sets varying.

This set of simulations show that consequences of the existence of friendship networks on viability of irrigated systems seem not to be as strong as it was inferred from a first version of the model. But it is still an open question. These simulations show in fact only that structural parameters linked to friendship networks are not so important. But it could also be that these consequences balance one another. Conse-

Table 6
Frequencies of viable simulations according to homogeneity value.

Homogeneity value	Initial scenario C	Initial scenario D	Initial scenario E
true	4.5	42.5	62.5
false	2.8	45	69

quences of social networks have then to be addressed through the specific processes in which they are activated, for example in learning processes.

6. Prospects

This is hence a simulator of irrigated systems which specifically tackles the organization and coordination of farmers in a varying framework of collective rules. Neither individually based nor collectively constrained, both organization levels coexist and “co-evolve”. It is a good basis to explore different scenarios of individual behaviors and collective rules, thus allowing “learning by simulating” rather than “learning by doing” which has been over-practiced in the field of irrigation development. This model constitutes a virtual irrigated system which can already be used as a tool to test hypotheses of social organizations and institutions.

This is still a theoretical simulator somewhat specific to the Senegal River Valley even though it has been designed to be able to deal with other contexts. A comparison with gravity irrigation in other areas will allow us to tackle the question of its genericity. Another question raised by this kind of modeling is the acceptability of simulation outputs for people in real irrigated systems: do they recognize themselves in simulated farmers? This question, which is part of the question of validation of this model, constitutes the next step of our field work.

References

- [1] J.-P. Aubin, *Dynamic Economic Theory, A Viability Approach* (Springer, 1997).
- [2] O. Barreteau, F. Bousquet and J. Weber, Modes de gestion et viabilité de périmètres irrigués: questions de représentation, in: *Tendances Nouvelles en Modélisation pour l'Environnement*, ed. F. Blasco (Elsevier, 1997) pp. 153–159.
- [3] P. Boivin, I. Dia, A. Lericollais, J.-C. Poussin, C. Santoir and S.M. Seck, *Nianga, Laboratoire de l'Agriculture Irriguée en Moyenne Vallée du Sénégal* (ORSTOM éditions, Paris, France, 1995).
- [4] F. Bousquet, O. Barreteau, C. Mullon and J. Weber, An environmental modelling approach: the use of multi-agent simulations, in: *Advances in Environmental Modelling*, eds. F. Blasco and A. Weill (Elsevier, 1999) pp. 113–122.
- [5] J.-L. Boutillier and J. Schmitz, Gestion traditionnelle des terres (système de décrue / système pluvial) et transition vers l'irrigation. Le cas de la vallée du Sénégal, *Cahiers des sciences humaines* 23 (1987) 533–554.
- [6] R. Chambers, In search of a water revolution: questions for canal irrigation management in the 1980's, *Water Supply and Management* 5 (1981) 5–18.
- [7] J. Doorenbos and A.H. Kassam, Réponse des rendements à l'eau, FAO, Bulletin d'irrigation et de drainage n°33, Rome, Italy (1979).

- [8] J. Ferber, Simulating with reactive agents, in: *Many-Agent Simulation and Artificial Life*, eds. E. Hillebrand and J. Stender (IOS Press, 1994) pp. 8–30.
- [9] R.C. Hunt, Determinants of management form in canal irrigation, in: *Irrigators and Engineers, Essays in Honor of Lucas Horst*, eds. G. Diemer and J. Slabbers (Thesis Publishers, Amsterdam, The Netherlands, 1992) pp. 203–214.
- [10] K. Jensen, *Coloured Petri Nets: Basic Concepts, Analysis Method and Practical Use*, Vol. 1, EATC Monographs on Theoretical Computer Science (Springer, 1992).
- [11] S.A. Kauffman, Principles of adaptation in complex systems, in: *Lectures in the Sciences of Complexity, SFI Studies in the Sciences of Complexity*, ed. D. Stein (Addison-Wesley, Longman, 1989) pp. 619–713.
- [12] P.-Y. Le Gal, Gestion collective des systèmes de culture en situation d’incertitude: cas de l’organisation du travail en double culture dans le Delta du Fleuve Sénégal, Thèse de doctorat de l’Institut National Agronomique de Paris-Grignon, Paris, France (1995).
- [13] A. Lericollais, Risques anciens, risques nouveaux en agriculture paysanne dans la vallée du Sénégal, in: *Le Risque en Agriculture*, eds. M. Eldin et P. Milleville (ORSTOM, Paris, France, 1989) pp. 429–436.
- [14] A. Lericollais and A. Sarr, Histoires de périmètres, in: *Nianga, Laboratoire de l’Agriculture Irriguée en Moyenne Vallée du Sénégal*, eds. P. Boivin et al. (ORSTOM, Paris, France, 1995) pp. 5–36.
- [15] M. Niasse, Les périmètres irrigués villageois vieillissent mal; les paysans se désengagent-ils en même temps que la SAED?, in: *La vallée du Fleuve Sénégal*, eds. B. Crousse et al. (1991) pp. 97–115.
- [16] E. Ostrom, *Governing the Commons: The Evolution of Institutions for Collective Action* (Cambridge University Press, 1990).
- [17] E. Ostrom and P. Benjamin, Design principles and the performance of farmer managed irrigation systems in Nepal, in: *Performance Measurement in Farmer Managed Irrigation Systems*, eds. S. Manor and J. Chambouleyron (IIMI, 1993) pp. 53–62.
- [18] J. Rumbaugh, M. Blaha, F. Eddy, W. Premerlani and W. Lorensen, *OMT, Modélisation et Conception Orientées Objet* (Masson, Paris, 1995).
- [19] M. Salem Murdock, M. Niasse, J. Magistro, C. Nuttal, M.M. Horowitz and O. Kane, *Les Barrages de la Controverse, le Cas de la Vallée du Fleuve Sénégal* (L’Harmattan, Paris, 1994).
- [20] S.M. Seck, Gestion et organisation des aménagements irrigués en exploitation paysanne dans la vallée du Sénégal, *Revue de géographie de Lyon* 65 (1990) 38–45.
- [21] C. Tarrière-Diop, La dynamique des GIE, village de Donaye, in: *Nianga, Laboratoire de l’Agriculture Irriguée en Moyenne Vallée du Sénégal*, eds. P. Boivin et al. (ORSTOM, Paris, France, 1995) pp. 339–373.
- [22] J. Weber, J.-M. Betsch and P. Cury, A l’interface hommes-nature: les ressources renouvelables, Rapport introductif au Colloque National Recherche et Environnement, Strasbourg, CNRS, Programme Environnement (1990) pp. 39–50.