



Suitability of Multi-Agent Simulations to study irrigated system viability: application to case studies in the Senegal River Valley

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Abstract

It is assumed that Agent-Based Modeling is a useful technique for water management issues. In particular, it may provide a suitable framework for representing irrigated systems. The objective of this paper is to demonstrate its potential for a specific use: research on irrigated systems' viability in the Senegal River Valley. The main assumption to be verified is that Multi-Agent Systems constitute a suitable architecture to study theoretically irrigated systems' viability using simulations. By using Multi-Agent Systems, virtual irrigated systems can be designed that might then be used as virtual laboratories. These virtual labs constitute an alternative when real labs cannot exist for some reason.

In this paper we report on experiments we have conducted using such virtual labs for exploring an Agent-Based Model through the simulation of scenarios. A scenario is defined as a triplet: an environment, a set of individual rules, a set of collective rules. It is evaluated according to the longevity of the irrigated system. An index is defined, based on the ratio of long-enduring simulations among a set of repetitions of a given scenario. Even if simulation results display significant diversity for a given scenario due to random factors in the processes simulated, the ratio of long-enduring simulations is repeatable. This entails to explore the overall behavior of the virtual irrigated system and to build theories concerning the viability of Senegalese irrigated systems. An example is given showing the need for strong coherence for a given environment among individual rules and collective rules.

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1. Introduction

Multi-Agent Systems (MAS) are increasingly used in the field of environmental and natural resource management issues (Doran, 1999; Ferrand, 1999; Moss and Davidsson, 2001; Bousquet et al., 2002). They constitute an effective resource because of their ability to represent complex systems, with interactions among dynamic and autonomous entities. In this paper, we consider their use as simulation tools: MAS are considered as models of real natural resource use systems. We have designed such a model based on a MAS, SHADOC, aiming at simulating irrigated systems in the Senegal River Valley (Barreteau and Bousquet, 2000).

However, such simulation models may have a variety of uses. Three possible main uses are mentioned in literature (Barreteau et al., 2001): research, education and decision support. When complex systems are at stake, there is an urgent need for the availability of new tools that allow for the simulation of scenarios, either for discussion or for exploring and analyzing the consequences of specific sets of rules. These complex systems are indeed difficult to understand or analyze with more classical and disciplinary frames. The relationship between these scenarios and some characteristics of these systems can hardly be explored through direct measurement on the systems, notably because of a lack of external control on these real systems.

We used SHADOC as a research support tool for a specific issue: irrigated system viability in the Senegal River Valley. Our purpose is here, through the description of this use of SHADOC, to explain how theories involving complex systems may be built by exploring a virtual system with simulations. Simulations based on scenarios defined as triplets {set of individual rules, set of collective rules, environment} lead to describe the overall behavioral patterns of the virtual system, interpreted as theories for real irrigated systems hereby represented. Exploration of specific scenarios is beyond the scope of this article and is analyzed in (Barreteau and Weber, 1998). We show however in this paper that use of simulations on this virtual irrigation system is meaningful and provides questions and frames for future thematic research.

We first describe irrigation in the Senegal River Valley and its main issues, and then the MAS designed to represent them. The simulations of scenarios on this virtual irrigated system provide the possibility to classify them according to a longevity index, and then discuss their viability as an issue of coherence among sets of individual and collective rules in a given environment.

2. Need for a simulation tool to study irrigation viability

The Senegal River Valley is a location of great interest to the irrigation engineer: it brings together availability of water in the river for pumping, good soil and excellent

climatic conditions for rice cultivation, as well as the manpower necessary to do the work. That makes it a good place to test ideas on scheme design patterns. The last few decades have shown, however, that even if some results have been reached, the expected level of development has not been attained, especially as regards yield and cropping intensity, which are much lower than planned. No really satisfying answer has been found to explain these failures, since most diagnostic studies are based on disciplinary research.

There is therefore a need for new tools dedicated to irrigated system applications, that can be used for work on simulating scenarios and proposing new insights on irrigated systems.

2.1. Development of irrigated systems in the Senegal River Valley

Irrigation practices in the middle Senegal River Valley developed rapidly from the mid-70s and especially during the 80s, ranging from 9000 ha covered with a developed and operational network in 1975, to 35,000 ha in 1988 (Seck, 1990). The development and the management of irrigated schemes has followed ever-changing trends, each one depending on concepts formalized far from the Valley, in Europe or in Dakar, for example. After a first wave of large-scale irrigation schemes, usually consisting of 1000 ha, with overall centralized management by SAED,¹ the parastatal company, came the period of PIV: simple small-scale schemes with no drainage, poor leveling, and management by a water users' association. This type of scheme has been implemented in different ways, depending on the donor agencies involved, the NGOs implementing the project and the consulting firms in charge of its design. The late 80s and the 90s saw the arrival of the so-called "intermediate schemes", which have sought to learn from the mistakes made during earlier experiments (Scheer, 1996).

Most schemes developed since that time have been abandoned or have been redesigned at least once. They are underused in relation to their design standards, regardless of their conception pattern. Moreover, the initial targets for irrigation development in the Valley have by no means been reached. Despite generous funding, irrigated areas are much smaller than originally envisioned. Furthermore, those systems that do function are only partially used for one cropping season instead of the two initially planned (Lericollais and Sarr, 1995).

Therefore, many experts have gone there to study some of these cases. The background of the experts very often influenced their diagnostics. Factors such as country, institute or scientific discipline, and questions they were paid to answer, weighed on their diagnostics, which ranged from bad yields, to trade problems, credit crises, poor maintenance of infrastructures, or land tenure disputes (Mathieu, 1995; Westster et al., 1995). Some have also pointed out the risks of soil degradation, salinization and sodization, if present practices are continued (Boivin, 1997). During the

¹ Acronym for "Société d'aménagement et d'exploitation des terres du Delta et de la vallée du Sénégal et de la Falémé", the company which had a major role in the development of irrigation in the Senegal River Valley and plays an advisory role to farmers and management of main infrastructures.

2002 rainy season, hardly any plots were cropped in the middle valley because of difficulties in accessing loans.

Each diagnosis is right when looked at within the strict framework of the issue dealt with. The questions they address are interconnected. Each one provides a particular perspective on the overall problem: the viability of these irrigated systems. Irrigated system viability is the issue we want to address here with a specific tool and method to study it.

In this paper, the viability of an irrigated system is understood as *its capacity to remain functional under given complex initial conditions within a given context*. Dealing with the viability of a system is equivalent to verifying the existence of a viable path for this system, among the set of its possible states, and with given initial conditions and constraints such as collective rules. We have to design a tool that can deal with a set of possible paths according to these initial conditions and constraints. Simulation models are good candidates since they can handle scenarios and system evolution.

The wide range of diagnostics available is due in part to the complexity of irrigated systems, which encourages experts to focus on only one part of the problem, making it easier for them to manage. Therefore, we need to deepen our knowledge of what makes irrigation systems complex.

2.2. Complexity of irrigated systems

There is a large number of definitions of irrigated systems in the literature available (Ostrom and Benjamin, 1993), each one combining, more or less, the same components. In this paper, we will use the following definition: a gravity-irrigated system is a network of canals that bring water from one or several sources to plots for agricultural production by farmers. These farmers may be grouped into producer organizations, and trade among themselves and with other people outside the system. The whole may or may not be managed by a users' association. This is where many interactions take place between individual and/or collective actors, either directly or via the environment.

In the case of the Senegal River Valley, complexity stems from the existence of different levels of organization that structure certain parts of schemes as well as groups of actors. The many kinds of interactions among these different elements add to this complexity. Fig. 1 shows the different elements that typically make up an irrigated system in the Senegal River Valley.

The organizational levels of stakeholders are linked to levels of organization of elements to be managed in the scheme:

- Each farmer cultivates one or more plots in at least one scheme and belongs to one or several groups to obtain loans and inputs, since only GIEs² are allowed to benefit from agricultural loans distributed by the bank.

² French acronym for “Groupement d'intérêt économique” (economic interest group), a wide-spread type of legal collective entity in Senegal.

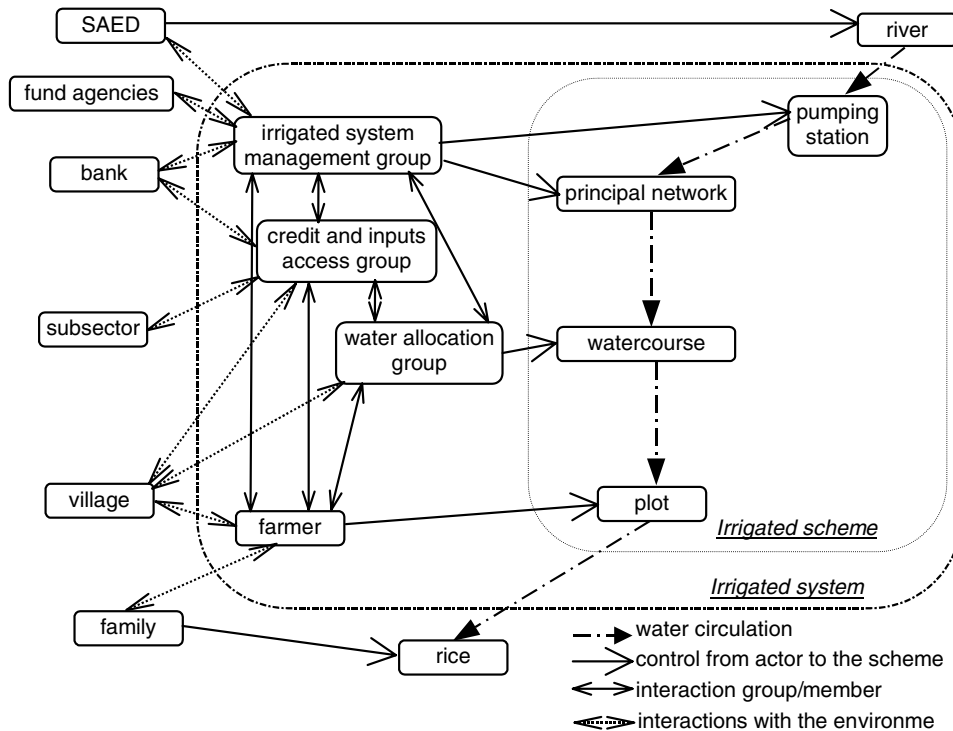


Fig. 1. Archetype of irrigated systems in Senegal River Valley (from Barreteau and Bousquet, 2000). SAED stands for “Société d’Aménagement et d’Exploitation des terres du Delta et de la vallée du Sénégal et de la Falémé”, the local state-owned society for territory management.

- Every farmer whose plot is dependent upon the same watercourse belongs to a users’ water allocation group. This role is very often carried out through the management of a water turn, or some slight variations of this concept. But it is sometimes carried out through a free access policy.
- Every farmer whose plot is in the same scheme belongs to a users’ group or a federation of users’ groups whose goal is the management of the whole irrigated scheme and, in particular, the operation and maintenance of pumping equipment and the principal canal network.

These three categories of groups may be assembled into only one or two groups. This depends on the system type: within large schemes, roles are separated, whereas in small ones they used to grouped together. In this case, one single group is endorsing two or three roles. For example, one group is in charge of supervising operation and maintenance of pumping equipment and the main canal, as well as of obtaining credit from the bank and distributing loans to its members.

The various types of interactions taking place in these systems among stakeholders and/or groups are not always formalized. They may be classified into four categories:

- direct interactions for service or information exchanges
 - *A farmer who has the water turn may allow another farmer, whose plot is along the same watercourse, to take water at the same time.*
 - *One farmer repairs the motorcycle of another farmer, who will work on his plot.*
- interactions through existing groups in relation to the structure of the irrigated system
 - *Each group is acting according to a set of rules and customs. For example, some credit groups grant credit to their members if these members are not too heavily indebted as a whole. This may explain the fact that some farmers might not receive credit even though they have paid off loans from previous seasons.*
- interactions through institutions external to the irrigated system such as the village or the age group to which farmers belong
 - *Conflicts relative to the scheme may be settled within the local institutions of age groups.*
- interactions through the scheme
 - *When a farmer along the canal takes water, another farmer further downstream may no longer take water at his own pace.*

It is important to differentiate these four kinds of interactions since they are constitutive of the complexity of irrigated systems. Interaction of one kind may attenuate or reinforce interaction of another kind.

2.3. *Requirements for a simulation tool*

The origin of the work described in this paper is the assessment of the hypothesis of a relationship between these different types of interactions and the viability of irrigated systems. More than “simply” representing irrigated systems’ complexity, it is a matter of finding out processes through which this complexity might influence irrigated system viability. We describe here the reasons for looking for new simulation to be able to conduct experiments for that purpose.

A first range of solutions would rely upon field experiments on specific sets of individual and collective behavioral patterns, for loan repayment for example. In the context of the Senegal River Valley already described, for a given irrigated system, sets of initial conditions contain at the least individual patterns of behavior on irrigation practices, as well as rules of cooperation with others and collective rules of management. To evaluate their consequences, these parameters would need to be controlled, which, besides being an extremely complex task, would lead to cumbersome and morally questionable experiments. Moreover, the relevant time steps in the evolution of irrigated systems are to be counted in decades. In fact, the assessment of the implementation of specific collective rules with respect to given individual behavioral patterns using real experiments cannot be seriously considered.

Another approach would be to compare information concerning the past and present states of various irrigation systems from existing data that is quite abundant for this part of the world. But even if they would give the appropriate information, it

would never be more than a comparison of static states, whereas the question of viability is, by nature, a dynamic one.

Therefore, at least for people external to the system, dealing with its viability implies the use of a simulation tool: a virtual irrigated system. This system should be able to explore consequences on the longevity of irrigated systems scenarios based on individual behavioral patterns, collective rules and environment setting. The results of these simulations on the virtual irrigated system may then pave the way for interpretation and further more analytical work on the real irrigated systems.

This implies the challenge of developing a model or a tool which takes into account social as well as agronomic and hydraulic dynamics, which is a central part of our research since few such experiments of using cross-disciplinary dynamic models in the field of agricultural systems are reported to give satisfactory results (Dent et al., 1995). This tool must be capable of simulating scenarios based on collective rules to be tested with varying hypotheses of individual behavioral patterns in a rather complex context, since interactions may lead in many directions. Therefore, it must not be too complex a tool so that the results of simulations might be usable: a 1:1 model would be quite adequate as a representation of reality but of no use in understanding it. This tool must also be dynamic in order to represent the path taken by the virtual irrigated system over time. At present, this raises two challenges for such a tool: the possibility of representing a complex system, and its suitability for studying the link between the system's viability and complexity based on various interactions. The first one has already been tackled (Barreteau and Bousquet, 2000). The central focus here is the second challenge, which implies that the model designed should be able to handle assumptions concerning modes of interaction among individual and collective behavioral patterns with a view to viability. Such a tool has to be able to bring coherent results that are capable of backing up the design of discourse on viability of irrigated systems. However, for the sake of explaining how our model is satisfying this second challenge, we will first go through a brief description of it.

3. Building a model

We will now give some details on the development of such a model: model choice and the building of the model with a special focus on how social dynamics are to be taken into account.

3.1. Choice of a Multi-Agent System type of model

Taking into account social factors in agricultural system models is in itself a difficult task. For this purpose, standard methods range from easy-to-use economic models that are built around strong hypotheses of behavioral patterns, to anthropological models that differentiate among individuals but which are of no practical use. Rule-based models and, among those, expert systems (Dent et al., 1995) provide another avenue of research. These have the advantage of enabling the constitution of a single framework to represent the whole system, putting aside the question of

coupling or integrating several disciplinary sub-models. There are, however, some limits to such tools when they are applied to agricultural systems: they require a large amount of knowledge, and there are not always experts available whose knowledge of the system could be inputted in the model.

Work in artificial intelligence may provide solutions to overcome these obstacles. When data exist but expert(s) needed to interpret them are not available, or when the set of rules is not complete, neural networks enable the system to learn new rules based on observed experiments (DeClaris and Su, 1993). Certain hypotheses of economic models can be simplified using neural networks, especially those concerning utility maximization behavior (Margarita and Beltratti, 1993). This method retains certain black box characteristics, which poses a problem for interpretations of collective rules and individual behavior.

Another solution lies in the refinement of expert systems using architecture based on object-oriented and specific task approaches: an object or agent task, aimed at solving the problem, generates and controls several task specific sub-objects or sub-agents. An application of this method for irrigated wheat management implements three communicative agents that, respectively, generate, test and critique management plans (Schroeder et al., 1994). These agents currently behave according to other models for which the same problems occur: they may or may not take social factors into account satisfactorily.

Expert systems are not the only rule-based modeling method. Agents may be used with another purpose in mind. Multi-Agent Systems (MAS), issued from work in Distributed Artificial Intelligence, may be used to solve distributed problems, as for the previously cited example or to represent components of the system.

A MAS is made up of an environment in which certain objects are located. Among these, the agents are able to perform some actions on other objects, thus at least partially perceiving their environment and communicating among themselves. Agents act and communicate according to their own goals and representation of the system, be it wrong or right (Ferber, 1999). They actually are autonomous computerized entities that interact. They may represent a task, as they did in the past. They may also represent a knowledge source. These MAS are currently multi-expert systems, with each agent relying on a sub-model that gathers the knowledge of a particular expert. Such applications have been implemented in several cases in the field of agriculture, such as coordination between irrigation and weed processing (Batchelor and McClendon, 1992), or cattle raising and pasture management (Hochman et al., 1995). They may finally represent any component of a system. We will now focus on this last type of MAS.

In the case of simulation of agricultural systems, an agent may represent whatever the modeler wants it to represent: a farmer, any individual, group of people, field, animal, etc. The condition is that the modeler is able to make hypotheses on rules governing their behavioral patterns. Since one challenge is to represent social dynamics, this representation does not necessarily assume that farmers would optimize any utility function. It can have adjustable levels of differentiation among the behavioral patterns of farmers: this depends on the knowledge of different behavioral patterns and on the capacities of model users to analyze simulation results.

Currently, MAS ally advantages of Cellular Automata and Multilevel modeling, since they are able to represent both interactions among individuals and among different levels of organization (Gilbert and Troitzch, 1999). Interactions among individuals with their own rules of behavior lead to emergent properties of a group of these individuals, which in turn influence individual behavioral patterns, whether the group be agentified or not (Rouchier et al., 1998). Furthermore, they are reported to be good at dealing with system dynamics (Kohler, 1999). In addition, they do not necessarily separate social from biophysical aspects in the modeling process as regards coupling techniques, since the core of modeling is the representation of processes at stake in the dynamics of the system under study.

Dynamically, each agent of the model, be it a farmer or a group, perceives a modification of its environment, such as an amount of water available, and receives messages from other agents, such as an agreement to share a water turn. The agent then reacts to these stimuli by acting on the environment and sending messages to other agents according to its own methods and characteristics. Hence simulations may follow different trajectories, for each agent as well as for the whole system, according to the occurrence of different events.

The stimuli perceived and taken into account by agents come in various forms: state of the environment, message, opinion of members (for a group). All are possible within the same modeling architecture.

3.2. *From field to model*

The irrigated systems of the Senegal River Valley described above are represented in just such a Multi-Agent System called SHADOC (French acronym for *hydro-agricultural simulator describing organization and coordination modes*). This model, which is fully described elsewhere (Barreteau, 1998; Barreteau and Bousquet, 2000), is based upon the assumption of the irrigated system as a place for acquisition and allocation of water and credit. It has been developed, in interaction with field studies in several steps, as a *companion modeling* (Bousquet et al., 1999).

From now until the end of this section, we are dealing only with computerized agents designed to represent real actors. Taken together, these agents constitute the Multi-Agent System designed to represent real irrigated systems. The object diagram (Rumbaugh et al., 1991) in Fig. 2 represents this simulated scheme. It is composed of a pumping station that supplies water to a main canal, which in turn delivers water to a collection of five watercourses along which plots are situated. The allocation of water among watercourses depends on their gate state and on the amount of water available from upstream to downstream. The allocation of water among open plots along the same watercourse is represented, emphasizing that upstream plots receive more water than those located downstream. Since this advantage of upstream plot is never the same from one watercourse to another, no formal rule could be inferred from observations in real systems. We have chosen the following rule of thumb: each open plot receives twice as much water as the next one downstream along the same watercourse.

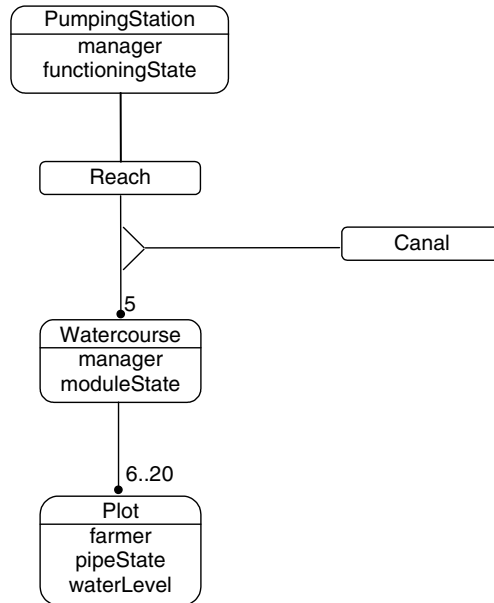


Fig. 2. Object representation of scheme structure (from Barreteau and Bousquet, 2000).

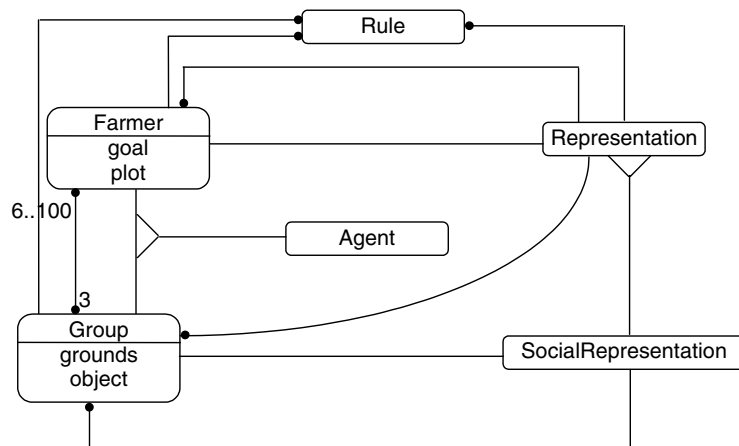


Fig. 3. Object representation of simulated society (from Barreteau and Bousquet, 2000).

The simulated society is also represented with an object diagram in Fig. 3. Each farmer is supposed to belong to three groups related to the irrigated system, one for water allocation among plots along the same watercourse, one for credit matters and one for pumping management. Each farmer has his own representation of the system, in which there is the supposed state of his plot, the supposed water availability

and a list of other farmers with whom he is ready to cooperate. This last component of each farmer's representation of the system consists of a friendship group that is specific to each farmer, within which he may exchange information and services. Each farmer also has a goal, among four categories identified through the analysis of interviews, which specifies the relative importance given to his plot through two items: the amount of inputs to invest and the priority given to the plot according to other activities.

Each group is autonomous by itself as an agent and therefore may act and communicate with other agents, groups and farmers. It may be described with its reason for existing (access to credit, water allocation, etc.) and its list of members. It also has a representation of the system, in which it keeps a record of the state of its relations with other agents it knows, such as possible debts for a credit group.

Lastly, each agent, be it a farmer or group has a set of rules that describes its behavioral patterns. The purpose of each rule in the set depends on the agent it concerns: individual rules for farmers or collective rules for groups. The purpose of collective rules also depends on each group's grounds for existence. Among these rules, each agent has a rule that evaluates *ex post* the course of a cropping season according to its own criterion, and another to change the rules in the event the criterion is not satisfied.

Dynamically, simulations are based on several time steps for agents to make their different choices:

- the day for choice of activity;
- the cropping season stage with activation of various specific rules such as pumping station start, irrigation, loan repayment;
- the whole cropping season for changing the set of rules.

One simulation may link several cropping seasons and stops upon the request of the user, or when the irrigated system is not used anymore. Typically, a simulated cropping season begins with a credit-seeking stage during which farmers request credit from either their group or from other farmers, according to their representation of chance of success. When a farmer estimates he is able to begin cropping, he sends a message to the group managing the pumping station, which allows him in return to get water during the season if his corresponding rule is verified. This group also has a rule to start the pumping station, which is activated when his representation of the system lets him know that the conditions seem to be fulfilled. The authorized farmers then begin to work on their plots: sowing, then irrigating according to their presence on the plot and their right or possibility to draw water.

By the end of the season, each farmer who has been able to sow a plot of rice gets his yield. This yield depends on several factors. When the plot is sown, the yield is initiated to a potential value depending on the level of inputs invested and on the choice of variety of rice (three options available with various cropping duration, the longest one being the most productive). Then each event of water stress during the season, as well as any lengthy delay in harvesting, induces a drop in this potential yield according to FAO equations (Doorenbos and Kassam, 1979). By the end of the season, the resultant yield is multiplied by a random factor to represent other events not simulated but having effects on real yields.

Those farmers who have taken out a loan may pay it off if they are able, and if they are accustomed to doing so. Then every agent evaluates the course of the season and, if not satisfied, changes his rules for the following season, imitating another agent who seems to have had good results. This imitation means switching his whole set of rules to the set of the agent imitated. The choice of the latter depends on a rule concerning changing rules: use the best set of rules according to the agent's own criterion of evaluation or the set of rules inducing the least changes among satisfying ones. Then a new cropping season may begin.

Such a model is currently an archetype for irrigated systems in the Senegal River Valley. Using this model, a Senegalese irrigated system can be represented by a computer model, in a way fitting formally the requirements for a simulation tool detailed above. Validation of the model, whether it fits the real systems or not, is not the point here: when the simulation tool is available the methodology is used for exploratory purposes and generates theories to ask new questions on the real systems. The acceptance of these theories and the possibilities to interpret them in relation with real systems is *the* stage needing that the tool is legitimate to the actors' eyes and is a valid representation of the real systems. In the case of SHADOC model, it has been checked through the use of a role-playing game explaining the content of the model (Barreteau et al., 2001). The central issue here is now to check whether this tool is able to generate meaningful theories based on simulations on this virtual irrigated system.

This tool produces simulations of the evolution of these irrigation systems. Our aim is to then use these simulations to better understand the dynamics of these irrigated systems, focusing in particular on their longevity. The challenge is to find out whether it is possible to sort out simulation results according to scenarios in spite of the interference produced by the use of random factors.

4. Relevance of simulations with this model

The range of variations and the sensitivity of the results to the choice of a specific scenario are now being put to the test to grasp the potential of the tool for generating theories.

4.1. Comparison with initial requirements

With this model, simulations are based on scenarios formalized as triplets of sets $\langle C, I, E \rangle$. C is a set of initial collective rules. This set includes notably a rule for authorizing farmers to draw water during a given season. I is a set of initial populations of individual behavioral patterns. Since each individual rule is described according to several possible types of behavior, the initial population specifies the ratio of farmers in each type at the very beginning of a simulation. This set includes for example the initial ratio of farmers cultivating their plot according to each type of goal. E is a set of environmental parameters. It includes among others the rate of daily decrease in water levels. This method of describing scenarios is well suited to the requirement of

taking into account individual behaviors as well as collective rules. This model is therefore able to simulate change in an irrigated system for various hypotheses of collective rules and populations of individual behavioral patterns in different environmental contexts.

Interactions implemented in the model can take several channels:

- between groups and pumping station, principal canals or watercourses;
- between each farmer agent and its plot;
- through each farmer agent's representation, which includes a rough estimate of the plot's evolution during its absence;
- through direct interactions between agents (within groups or friendship networks);
- through direct interactions between objects in the environment (plots, canals, watercourses).

Therefore, simulations with this model may grasp, at least in part, the consequences of the complexity and interdisciplinary nature of irrigation systems.

Several indicators are simulated by SHADOC: number of cropping seasons with number of plots cultivated, water consumption, number and topic of communications, evolution of the population of rules, and sum of each agent's financial resources. The first indicator is the most closely linked to the purpose of studying the longevity of irrigated systems, since it simulates the number of cropping seasons yielded by the irrigated system with a given scenario without the representation of any external support. Other indicators are more useful for understanding what is happening in the course of a simulation, and in particular, reasons for early ending of the whole system. The number of plots cultivated at each cropping season throughout a simulation is thus computed and stored. This provides a viewpoint on the evolution of the simulated irrigated system for given initial sets of collective rules and individual behavioral patterns. In formal terms, this viewpoint is a series of the number of plots cultivated per cropping season. These series are to be compared among scenarios, to check whether various scenarios lead to various series. However, repeated simulations of a given scenario must also be compared: random generators used throughout the simulation of their dynamics yield variations in simulation results as well. Both sources of variability must then be compared, so that one might be able to compare sensitivity of longevity to the choice of a given scenario using this indicator.

The question then is: can this simulation tool be used to speak about the greater longevity or viability of one scenario comparatively to another? This means comparing the “intra-scenario” and the “inter-scenario” variability of this indicator. For this reason, we investigated 100 scenarios selected randomly among the population of possible scenarios. Since several random numbers. These random factors represent aspects of the system that are either unknown or not detailed, as well as some known as uncertain. For example, activities outside of the irrigated system of each farmer are endorsed in this way. They are used in the course of a simulation. Each scenario has been simulated 20 times in the first round for 15 cropping seasons at most. More than 15 simulated cropping seasons would have little meaning since maintenance aspects are not taken in account. We mainly observed the phenomenon

related to our longevity indicator. Only results linked to this indicator are described here.

4.2. Classification of scenarios according to viability

Both kinds of variability are quite significant, as shown in Fig. 4. This figure features the evolution of three different scenarios, with 20 repetitions each. A selection of varying items describing individual and collective behavioral patterns in these three scenarios is found in Table 1.

Some scenarios result in 15 cropping seasons with a good ratio of plots cultivated, whereas others never go beyond the second season. The first graph shows both kinds of evolution for a given scenario. Intra-scenario variability is due to the existence of several possible paths of evolution for the simulated irrigated system in a given scenario. Random events occurring throughout the simulation process lead the simulated irrigated system towards one path or the other. Observation of indicators other than number of cultivated plots provides a description of what happened during the simulation: water consumption or topic and intensity of message exchanges during the last simulated cropping season of early-ending simulations help explain some of the non-viable paths. For example, Fig. 5 shows the evolution of messages exchanged dealing with pumping issues at each cropping season. The evolution of this indicator is also given for 20 repetitions of a given scenario. Each path followed by this simulated irrigated system has a rather constant number of messages exchanged on this topic at each cropping season, except for the last cropping season if the overall duration is less than 15. This indicates that the end of these paths may be linked to crises that may include problems with the pumping device. Another frequent way of ending is with crises relating to farmers' debts, which can be detected through the number of messages exchanged dealing with calls for funds.

The high level of inter-scenario variability is a cause for optimism on the possibility to use simulations outcomes to build theories on irrigated systems. But the magnitude of intra-scenario variability shows that the model is not suited to the assessment of scenario viability based on only one simulation. On Fig. 4, we also notice that the evolution paths of scenarios are either short or long; few are in between. Similar two-mode distributions are observed for nearly all scenarios: schematically, number of cropping seasons per simulation is either low or up to 15.

This qualitative classification of the evolution paths of a given scenario into two or sometimes three groups is indicative of a complex system. It may be explained by changes made from one path of evolution to another along different branches. This is due to small differences linked to random factors occurring at the beginning of and throughout the repetitions of the simulation of a given scenario. Viable paths may exist for some scenarios of initial collective rules and individual behavioral patterns, but the simulated irrigated system will not necessarily follow them. This raises the need to study the controls involved and those possible in irrigated systems so they may stay on the paths chosen.

This possibility for classification leads to another possible means for defining the viability of a scenario: the ratio of “viable simulations” for a given scenario in a set

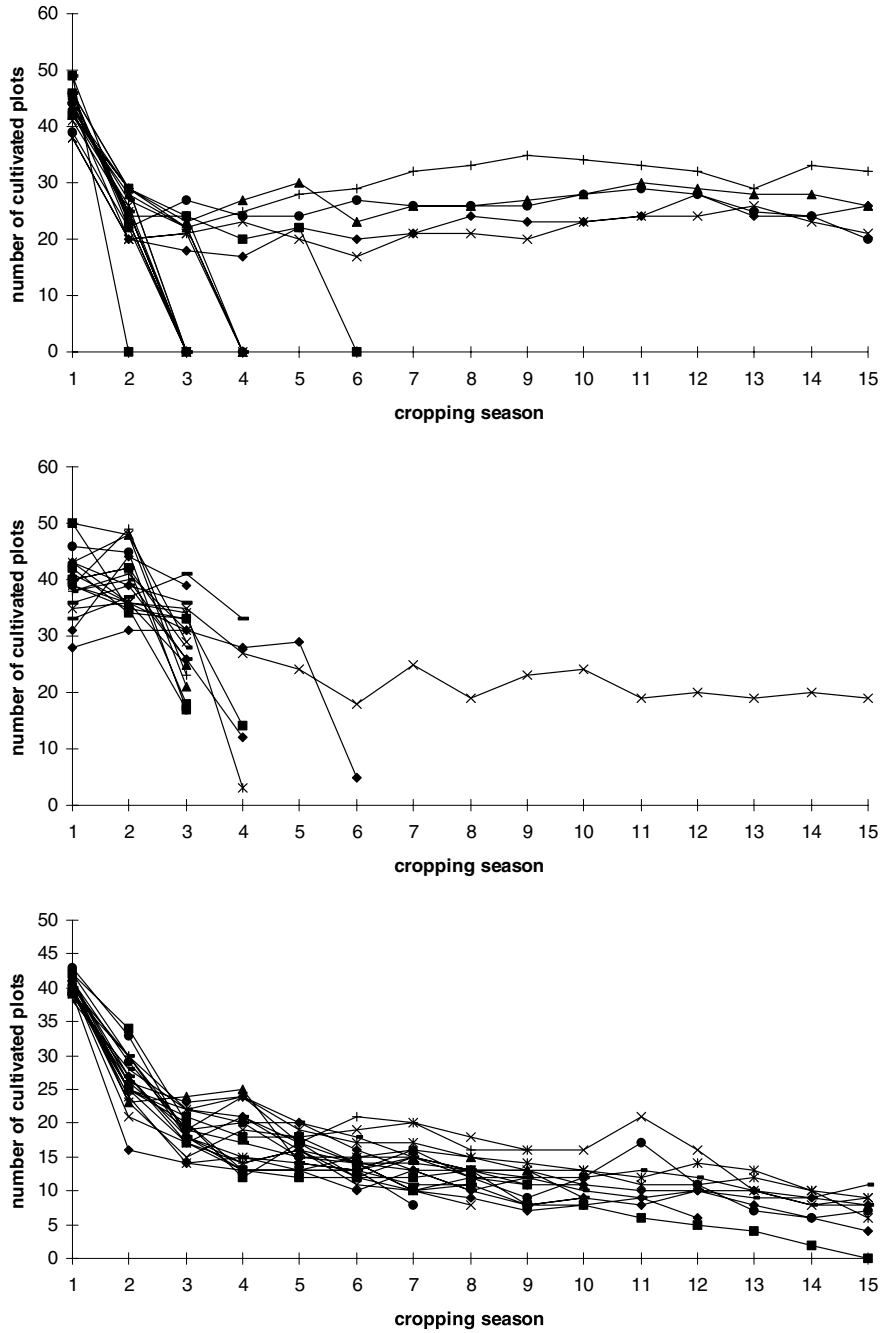


Fig. 4. Three different scenarios with 20 repeated simulations of the number of cultivated plots in each cropping season.

Table 1
Selection of items describing scenarios used in Fig. 5

Scenario	Pumping authorization	Goal for cultivating (percentage of farmer population)			
		Production	Food	Land	Waiting for job
1	Individual	29	37	5	29
2	Collective	16	3	48	33
3	Individual	43	26	14	17

“Pumping authorization” specifies whether or not a farmer is authorized to irrigate according to his own payment of water fees (“individual”) or payment by farmers along the whole watercourse (“collective”).

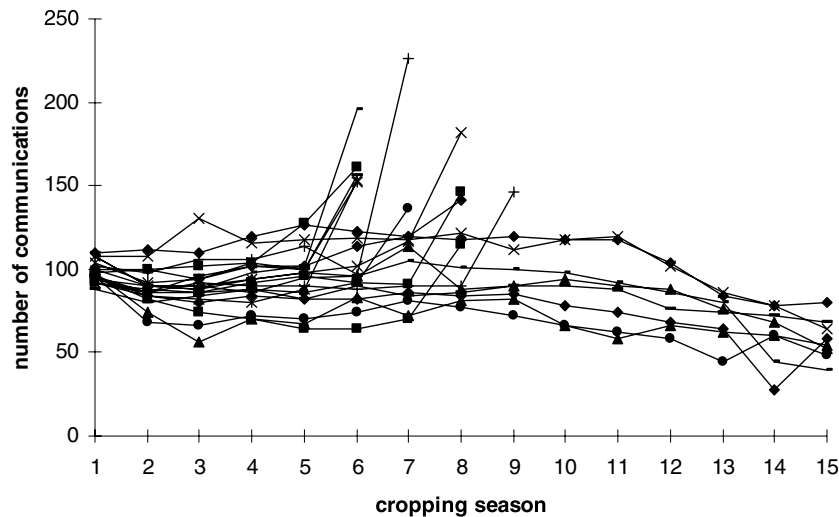


Fig. 5. Number of messages exchanged dealing with pumping issues per simulated cropping season.

of simulations. Instead of assessing the longevity of a simulated irrigated system within a given scenario through one simulation, we compare the proportion of repeated simulations which are long-enduring among a given set of repeated simulations. This entails first specifying what will qualify as a long-enduring simulation to be accepted as “a viable simulation”. This then leads to a more quantitative study. After the qualitative study, we put forth the hypothesis that these notions of viable simulations and of viable scenarios depend on the definitions of four thresholds:

- A simulation will be considered viable if there is a significant ratio of plots in the simulated irrigated system that are cropped during a minimum number of cropping seasons. This results in the definition of a threshold T_c for the minimum number of cropping seasons in one simulation and T_i for the minimum ratio of cultivated plots to consider a cropping season.
- A scenario will fall into one of three classes, defined according to two thresholds, T_1 and T_2 , and depending on the ratio of viable simulations among a set of

repeated simulations: a class of *non-viable scenarios* with very few viable simulations ($<T_1$), a class of *slightly-viable scenarios* with some viable simulations ($>T_1$ and $<T_2$), and a class of *viable scenarios* with a majority of viable simulations ($>T_2$).

In order to define these thresholds, each scenario of the initial set of 100 has been simulated 100 times in 5 series of 20 repetitions. These series have been used to define the thresholds. The first four series (sets 1–4 of Table 2) have then been used to define the class of viability of each scenario, while the fifth has been used to study the stability of this classification according to the set of simulations.

Threshold T_c has been fixed to $T_c = 6$ in order to get around the problem of initial interference, and because it improved the stability of classes of scenario viability. It means that a simulation which stops with less than 6 cropping season simulated is not viable.

As for T_i , we used $T_i = 0.25$, in reference to parameters in the model: when the group that manages the pumping station has a starting rule depending on ratio of farmers ready to cultivate, it starts with at least 30% of farmers ready to cultivate. So, a simulation is reputed to be viable if it reaches at least 25% of cultivated plots in at least one cropping season, starting with the sixth one and including those following it.

T_1 has then been set at 5%, which means that scenarios with no more than one viable simulation out of 20 are in the *non-viable* class. T_2 has been chosen to optimize the stability of population of the “viable” and “slightly-viable” classes for the first 4 series of 20 simulations: for each of these 4 series, class of each scenario has been determined with various values of T_2 around 10, the class of each scenario has also been determined with the same values of T_2 using the 4 series as a single one, we have then chosen the value of T_2 minimizing the number of error in classification. This gives $T_2 = 9$.

The classification of scenarios has then been determined with the four series considered altogether, and compared to the classification obtained with the fifth set of simulations alone. The number of scenarios with a class different than that defined by the first 4 sets altogether is reported for each set in Table 2.

It is therefore possible to classify scenarios of our random sample in three classes of viability. This classification was then acceptable and made it possible to separate scenarios: these simulations may lead to discussion on the viability of a scenario.

Table 2
Number of misclassified scenarios among the 100 randomly selected

	Set 1	Set 2	Set 3	Set 4	Set 5
Errors between class 1 and class 2	1	3	2	1	3
Errors between class 0 and class 1	3	3	3	8	4
Total	4	6	5	9	7

Comparison is done between the class of viability determined by the ratio of viable simulations (as defined in text) for each set of 20 simulations and the class of viability determined by the ratio of viable simulations for the first four sets considered as a whole.

4.3. Towards the building of theories on irrigated systems

Simulations make characterization of the longevity of irrigated systems possible according to various scenarios of use and design. This model can thus be used to build theories, working upon this classification, about links between individual/collective behavioral patterns and viability of irrigated systems in a given environment.

As an example of discussion that may be sparked thanks to the use of this tool, a possible correlation between viability and some particular rule has been explored, as well as the effects of variations of one particular rule on the viability of scenarios (Barreteau, 1998). Particular issues such as the (non-) existence of a set of collective rules or population of individual behavioral patterns that would guarantee the viability of the system have also been explored (Barreteau and Weber, 1998).

An example of what we call theories, which simulations helped to produce, concerns the influence of heterogeneity of population of goals on viability of the irrigated system. In the model, the class Farmer has been described as having one goal among its attributes. This goal is chosen from among four possibilities that have more or less intensive needs concerning money and availability of labor.

One parameter of scenarios is the existence and type (random or dependent on goal or agricultural activity) of external incomes for farmers. Results of simulations in Table 3 show that, among scenarios having the possibility of outside incomes, those with populations that are either very heterogeneous or very homogeneous in one of these goals are more non-viable than those with little heterogeneity. However, a homogeneous population of farmers is more often sought after, especially in the case of centralized management, since it lends itself to easier scheduling of plot irrigation by each individual.

Goals set by farmers play a part in several processes during the course of a simulation, and usually concern access as well as use of credit and water. If the population is strongly heterogeneous, coordination problems among farmers could appear as a result of conflict over water access, which is amplified due to irrigation needs at different paces, thus inducing lower viability. The minimum level of heterogeneity necessary may be explained as a collective risk-management strategy. Such phenomena using exchanges through social networks have been observed by anthropologists (Hegmon, 1989): members of the network who obtained better results during one season or in one stage of the season may help others. This may result in specializa-

Table 3

Contingency table for correlation test between the degree of homogeneity of farmers' goals and class of viability, for scenarios with external incomes

	Non-viable	Slightly-viable or viable	Total
Heterogeneous	13	10	23
Average	7	16	23
Homogeneous	17	9	26
Total	37	35	72

Probability of exceeding associated χ^2 test: 0.96.

tion of farmers according to their goals and other activities. Such cases of specialization have been observed in the field, and tend to strengthen a theory that *a little heterogeneity is needed for viability in an irrigated system*.

In any case, the validity of such theories is not proven by this means. Theories may appear to be wrong when confronted with new field research, or may seem to be in contradiction with other accepted theories. Simulations with this model are a support for the exploration of complex dynamic questions and a frame to induce new thematic field work. It allows to sort out among the many possible paths for thorough thematic research.

5. Conclusion

In cases of irrigated systems in the Senegal River Valley, we have tested a new kind of simulation tool. This tool can deal with some of the complexity of real systems and is able to take into account the links between coordination patterns of relations connecting individuals and groups, and the viability of these systems. Simulations with this tool on a random sample of scenarios show that it is possible to classify them according to an indicator of longevity. This classification together with the analysis of path taken by specific simulation processes provide the basis to build theories upon these virtual irrigated system dynamics, proposing ways of further thematic research on real irrigated systems. The role of the virtual irrigated system is heuristic, providing new ways of looking at irrigated systems and limiting impacts on real systems. The issue of validation is beyond that purpose of ability of generating new thinkings on irrigated systems. Validation is another stage and is rather an issue of legitimacy, related to the methodology of use for such an application, and must be carried out (Barreteau et al., 2001).

Scenarios defined as triplets of set of collective behavioral patterns, set of individual behavioral patterns and environment characteristics, can be separated according to an indicator of viability, expressed as a ratio of simulations above two thresholds. The virtual irrigated system has thus the behavior of a complex system, with various possible paths of evolution for one given scenario, as real irrigated systems have.

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