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Environmental Modelling & Software 18 (2003) 413–427

Environmental Modelling & Software

www.elsevier.com/locate/envsoft

SINUSE: a multi-agent model to negotiate water demand management on a free access water table

S. Feuillette [a] [1], F. Bousquet [b,*], P. Le Goulven [c]

[a] LIA-GEODE, IRD, 32 avenue Varagnat, 93143 Bondy, Cedex, France
[b] CIRAD IRRI, Chatuchak, P.O. Box 9-159, 10900 Bangkok, Thailand
[c] DIVHA, Maison des Sciences de l'Eau, IRD/MSE, BP 64501, 34394 Montpellier, Cedex 5, France

Received 13 May 2002; received in revised form 2 December 2002; accepted 9 December 2002

Abstract

Many water tables are currently overexploited throughout the world. This situation raises the question of their management. Integrated management of such systems, established in both supply and demand areas, calls for thorough knowledge of the functioning of both the water table and its users, so models are usually required. This study is based on the case of the Kairouan water table, located in Tunisia, which has been continuously and globally decreasing for more than 20 years, due to overexploitation by private irrigators. The field study led to the hypothesis that the dynamics of the system is heavily influenced by local interaction between the resource and its users, and by direct, non-economic interaction between the farmers. The literature shows that several kinds of model have already been used to represent interaction between a water table and its users but none of them are able to take this kind of social behaviour into account. The simulator of a water table and user interaction (SINUSE) based upon multi-agent systems enabled us to overcome these limitations. This model proved to be very useful for representing a complex and distributed system such as the Kairouan water table. It enabled us to explore the interaction between the physical and socio-economic components of the system and to conclude that local and non-economic behaviour do have a major impact on the global dynamics of the system and must therefore be taken into account. The management interventions simulated with the SINUSE model have raised interesting questions, leading to the conclusion that this model could provide a useful tool for negotiating the integrated management of the water table system. Though this model is rather specific, the approach developed could be transferred to other water table systems, to improve the knowledge of their functioning and examine the possible impacts of different management tools.

Keywords: Water table overexploitation; Irrigation; Multi-agent systems; Water demand

1. Introduction

Groundwater is the most abundant fresh water resource directly available on earth. Nowadays, numerous water table systems suffer from overexploitation (Berkoff, 1994), which introduces a growing threat of non-viability. Indeed, such situations can provoke salt-water intrusion into the groundwater or massive increases in water extraction costs, leading to non-viable situations over the short-term. Moreover, even when such problems are not encountered, the continuous drop in a water table raises the long-term question of transmission of the resource to future generations.

So it is important to think about the management of these systems. As acting upon the water resource—by replenishing the water table or supplying water from other sources—is increasingly difficult and costly, the capacity to control water demand becomes a key issue for the sustainability of these systems (Bhatia et al., 1995). Several kinds of tool are used to manage water demand (Montginoul, 1998) and have been applied to water tables: technical tools, such as microirrigation, to improve irrigation; economic tools such as fees, taxes (Kosciusko-Morizet et al., 1998), water charges (Blomquist, 1992) or water markets (Meinzen-Dick,

* Corresponding author. Tel.: +66-2-942-7025; fax: +66-2-561-4894.
E-mail addresses: feuillette.sarah@aesn.fr (S. Feuillette); bousquet@cirad.fr (F. Bousquet); patrick.legoulven@mpl.ird.fr (P. Le Goulven).
[1] Tel.: +33-1-43-73-01-52; fax: +33-1-48-47-30-88.

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doi:10.1016/S1364-8152(03)00006-9

1997; Palmer Jones, 1994); and non-economic tools such as access rules (Teerink and Nakashima, 1996), quotas, education (Nagaraj et al., 2000) or contracts.

The effectiveness of these different tools varies, depending on water demand elasticity to price, water scarcity, users' behaviour, as well as the political, cultural and institutional environment. For example, the use of efficient irrigation technologies does not necessarily prevent an increase in global withdrawals if farmers continue to extend irrigation (Nagaraj et al., 2000). In several cases, water markets for groundwater have also proved to be ineffective (Meinzen-Dick and Rosegrant, 1997; Montginoul and Strosser, 1999). In fact, to obtain the desired impact, water demand management tools must not only correspond to the situation but also meet the approval of all users, who must clearly understand how they work (Montginoul, 1997), or even be the instigators of their use (Briscoe, 1997). Users must be aware of the problem of overexploitation. But on a water table, this is made difficult by the fact that users neither see their resource nor the effects of any interventions and consequently find it difficult to perceive the necessity of managing the system. More generally, water demand management tools are difficult to apply on groundwater: users can access the resource directly and are scattered over a large area, so control is costly and difficult; furthermore most are not willing to pay for water, especially as water withdrawal is already a costly operation. Finally, most water table users do not act as if they were sharing the same resource, despite the confusion caused by Provencher and Burt (1994), arising from of Hardin's famous "Tragedy of the Commons" (Hardin, 1968), most water tables are not common resources as described by Ostrom (1990), but are, on the contrary, free access resources. It is therefore particularly difficult to convince users of the need to manage the resource and to get social approval for any demand management tools.

Faced with this kind of problem, the authorities need models not only to evaluate the possible effects of different kinds of controls on water demand but also to communicate with the stakeholders. This requires that social aspects be taken realistically into account in the dynamics of the water table system.

In fact, several models are already used to compare different management tools. Some rely on disciplinary approaches (economic, agronomic or agro-economic), which does not take interaction between supply and demand into account, while others overcome this limitation by representing the functioning of both the resource and the social system. The literature on water table management shows that the demand side of this latter category of models, generally founded on a coupling of water table mathematical models with economic models, is based on rational economic behaviour of the users. Consequently, they are limited by the unbounded economic hypothesis of rationality. Moreover they do not take non-economic interactions between users into account, and are practically incapable of representing long-term strategies (such as investment strategies). Yet, in the case of the Kairouan water table, considered as representative of numerous overexploited water tables, our field study demonstrated that: (i) the Kairouan water table is a free access water table; (ii) users barely perceive the water table and are not conscious of the growing overexploitation problems; (iii) water demand is driven by long-term investment strategies rather than by short-term withdrawal behaviour on a stable number of wells; and (iv) the dynamics of the system is influenced mainly by local and non-economic interaction between irrigators, such as imitation.

Thus, to study the influence of these interactions, we chose to build a model which aims to show the observed dynamics of the system to the stakeholders (including non-economic interaction and long-term strategies of users) and to explore the effects of different kinds of intervention. As multi-agents systems (Ferber, 1994) have proved to fit very well with these kinds of goals (Barreteau, 2000; Deadman et al., 2000; Janssen, 2003; Rouchier et al., 2001), we chose this tool to build a model capable of representing a distributed, complex system, where the simulated behaviours are based on field observations. First, the case study is described. Then, the modelling choices are presented, the simulation results are interpreted and the credibility of the model is assessed. Finally the use of the model is discussed.

2. Case study

The Kairouan water table covers an area of more than 3000 km^2 and constitutes the largest water resource of Central Tunisia. It is a renewable resource, which is mainly supplied by three watersheds: the Zeroud, the Merguellil and the Nebhana, which have been closed by dams since 1980s.

As the entire water table could not be covered by our study, we chose a particular zone of the water table, at the release of the Merguellil watershed, below the El Haouareb dam.

This study zone was bounded using physical, social, agronomic and administrative criteria. This very large aquifer comprises different interconnected levels. The water depth varies along an east-west gradient, from 20 to 80 m. The main user of this resource is agriculture, as it consumes 80% of the annual volume extracted. The rest is mainly used as drinking water and marginally for industry. Most of the irrigators extract their water directly from private wells, while a minority receive it through collective irrigation systems supplied by collective boreholes called public irrigated perimeters (PPI) which, until recently, were managed by public institutions. Responsibility is increasingly being transferred to the users, though the impact on farmers' behaviour appears to be limited.

Farmers frequently own several scattered plots, some of which may depend on a PPI, some may be irrigated by a well, and others not irrigated at all. Most of the plots are small, generally covering areas from 1–10 ha. Very few cover more than 50 ha.

As a consequence of the falling water table, most of the wells are apparently dry and deepened by manual boring. Nowadays, this kind of construction may reach 100 m in depth, and this depth is likely to increase as drilling techniques improve.

Though the number of private users is very large, the authorities know little about them, either in terms of numbers or behaviour. This makes it very difficult to evaluate the reaction of the system to a given management tool, especially since the system comprises numerous distributed elements such as the farms, the PPI, the water table depth (Feuillette et al., 1998). Our field study therefore aimed at improving knowledge of the water table, through a global approach to the system. We defined its boundaries, entities and the interaction linking the different components of the system to each other and to their environment. Several types of inquiry enabled us to characterise this system. As the groundwater is currently being studied and modelled by hydrogeologists (Nazoumou and Besbes, 2000, 2001), our study was able to focus on the users, taking advantage of results found on the resource.

A preliminary approach led us to a clearer view of the problems and to a set of hypotheses about the main interactions of the system. For example, it showed that the physical interaction between two wells can be neglected and that the drop in the water table is perceived by users on a large scale much more than locally. Furthermore, it showed that the salination process is not perceptible for the moment and is little understood by the authorities. It was therefore decided to neglect these two aspects in our representation of the system. Nevertheless, the salination process is taken into account as a long-run risk that motivates management intervention. This first approach also showed that several kinds of local, direct and non-economic interaction between farmers seemed to play an important part in the dynamics of the system. It was therefore decided to study them in more detail.

On this basis, detailed inquiries were made over 1 year on selection of representative farmers. In the meanwhile, statistical inquiries were made for 10% of the population of farmers. These different inquiries provided a lot of information. First, the data collected showed that agriculture is still traditional in this zone and are linked with the farmer's family: production is only partially intended for the market, the choice of crops and the techniques are frequently traditional, the family does most of the farm work and the budgets of the farm and of the family are mixed. Traditionally, a variety of crop is preferred to specialisation, to minimise climatic and economic risks. The main crops are wheat, barley and olives. On the farms, access to irrigation enables farmers to grow productive crops such as watermelon, tomato, pepper, apples or apricots, which are easy to sell and therefore facilitate the transition towards market agriculture. Furthermore, thanks to irrigation, the traditional crops are less risky as a lack of rain can be offset by complementary irrigation. Private irrigation is preferred to collective systems, where water must be paid for, and where the choice of crops and the economic results depend largely on water delivery constraints. Consequently, all the farmers try to access water by building their own well. But this operation is costly and risky, as it can fail if the aquifer is deep or inaccessible. In fact, farmers will only invest in well construction under certain conditions, i.e. if they have enough available area and enough money. Moreover, it is less risky to build a well on a plot whose neighbourhood already includes functioning wells, as this indicates that water is accessible. Furthermore, farmers seem to be socially influenced by the fact that their neighbours own a well. The different influences of the neighbourhood were associated in a single procedure called 'imitation' by which the farmer seeks 'worthwhile' plots according to his neighbourhood. In fact, nowadays most wells are found in the eastern part of the zone, which has been historically exploited by private irrigators, as the water table is less deep than in the western part.

Other direct interactions were brought to light by our inquiries, such as the teaming up of two neighbours to build a single well together when each one does not have enough money or land, or the annual exchange of plots between neighbours, paid according to the harvest. On the other hand, the land market is very limited, as farmers are traditionally very attached to their plots.

On the basis of these inquiries, we defined the different components of water demand, and improved our knowledge of the farmers' behaviour in terms of crop choice and investment decisions. We found in particular that water demand in the short as well as the long-term is more generally influenced by the choice of crops than by differences in the daily practices of the farmers, all the more as the studied area can be considered as an 'agrarian system' (as defined by Campagne, 1994), in other words a place where common environmental and historical constraints have crafted a society where practices and trends can be considered as practically homogeneous. Finally, it appeared that the strategies deployed by farmers to acquire irrigation, and in particular private irrigation, depend on a combination of local factors, such as their socio-economic and spatial situations, which differ from one another and are frequently based on economic and non-economic interactions with their neighbourhood.

3. Modelling the system

3.1. The choice of a modelling approach

Several kinds of model that attempt to represent the management of common pool resources, in particular in the field of water resources, can be found in the literature. They can be classified into three approximate types: (i) physical models centred on the dynamics of resources and that consider demand as a given parameter; (ii) agronomic, economic or agro-economic models centred on demand and that attempt to adapt water demand to a fixed amount of resource; (iii) mixed models that represent interaction between the functioning of physical and socio-economic systems, through a single mathematical language, through the coupling of several models or through multi-agent systems (MASs). The model we wish to build is of the third type, as we assume that local interactions between the water table and its users are of great importance.

In fact, up to now, water table management has been investigated by using hydrogeological models of the first type (Akhy et al., 1997; Besbes, 1975; Laurent, 1993), or simple calculations of water balance (Armstrong, 2000), or also economic and agro-economic models of the second type (Eheart and Barclay, 1990; Heikkila, 2000; Provencher and Burt, 1994). More recently, assuming that dynamic interaction between the water tables and its users must be taken into account, some mixed models have been built, above all coupling distributed water table models and agro-economic models (Cunha et al., 1993; Faisal et al., 1997; Mañas et al., 1999; Verbeek et al., 1996).

But these models do not represent observed human behaviour. Nevertheless, assumptions about the agents' behaviour may have a significant impact on the dynamics of the system, as Gintis (2000) has shown, on the basis of experiments comparing purely rational behaviour based on neoclassical economic theory with behaviour based on social and psychological descriptions. He has also demonstrated the weakness of models based on neoclassical economic theory. In farming systems more particularly, Dent et al. (1995) also highlight the inability of the neoclassical approach to model farmer decision-making. More realistic action models used in agronomy have been used to represent short-term strategies generating water demand on a farm (Sebillotte and Soler, 1998), and when coupled with a physical model of water resource, has already proved useful for building a mixed model of the third type (Lamacq, 1997). Still this kind of model does not represent interaction between users, and neither does it take multi-annual changes into account.

On the other hand, MAS have proved to be very useful for taking into account of several kind of anomaly that cannot be explained with other models (Bousquet et al., 1999), in particular in the field of common pool resources, where interaction between social and physical systems is often a key factor. More precisely, they have already been used to represent non-economic interaction between the actors (Barreteau and Bousquet, 2000). Indeed, on the basis of such a model, Rouchier et al. (2001) examined the dynamics of nomadic people of North Cameroon, comparing strictly rational behaviour with observed relationships based on traditional faith nets, and demonstrated the importance of the rationality described in a modelling system. Moreover Jager et al. (2000) have constructed a multi-agent simulation program taking realistic human behaviour into account through cognitive limited agents; they demonstrate the interest of incorporating a micro-level perspective on human behaviour to understand the processes involved in environmental degradation. On the basis of multi-agent simulators, Antona et al. (1999) have also shown how representing the limited perception of information is important, while Lifran et al. (1998) and also Balmann (1997) have shown the importance of neighbouring externalities.

Consequently, given the complexity, the spatial characteristics and above all the non-economic and interactive behaviour of farmers, the MAS were chosen, all the more as they are able to represent spatially and temporally distributed systems (Lièvre and Traoré, 1998). The data collected in the field were used to construct the simulator of a water table and user interaction (SINUSE), with a special focus on economic and social interactions, as we assume that they play a major part in the dynamics of the system.

3.2. A general view of the model

The SINUSE model is very specific to the case study. Nevertheless, its architecture and more generally, the modelling approach can be easily transferred to other cases. So this section will describe the main elements of the model without going to the level of detail that would permit replication. However, the model is available and downloadable on Internet (see subsequently). In the following sections, farmers, plots, perimeters and water tables will frequently refer to computer agents rather than components of the real system.

The main goals of the model were first to test the importance of local interaction between farmers observed on the field and second, to provide a tool to help the authorities in their search for a socially acceptable way of managing demand to protect the resource.

The model was implemented in the Smalltalk language in a simulation environment called common-pool resources and multi-agent system (Cormas),[2] using a Visualworks environment (Bousquet et al., 1998). This platform was built for the specific purpose of studying complex systems involving both natural resources and human societies. With Cormas, it is easy to create communicating and situated agents and to implement the control of simulation dynamics. Cormas also provides several ways to observe the simulation, in particular a spatial grid to visualise the spatial dynamics of the simulations, therefore avoiding the communication problems that frequently occur when modelling a field study with a computing specialist. Consequently it allows the researcher to build his own model. Furthermore, the scientific community working with Cormas has built up extensive expertise in natural resources management and modelling, which were useful for this particular study.

The main hypothesis of the model is that local interactions between users and between users and the resource do have major impacts on overall lowering of the water table. The model is then based on a series of assumptions, the most important of which are the following:

- The crop choices are based mainly on the status of the plot: whether or not it is irrigated, and if so by a well or by a PPI, whether or not it is owned by the farmer, etc. Other factors such as the market have only a minor impact on these choices.
- Before deciding to build a well on his own, a farmer must own at least 4 ha and have 65% of the money needed (the rest can come from the family, from the builder's credit or from any other kind of private loan), and he should first try to build it on a potentially attractive plot where the water table is not too deep.
- A minority of farmers are alike to run the risk of building a well in a place where functioning wells do not exist.
- Farmers will wait until they are heavily in debt before selling a plot, and this is mostly the case when it is their last plot.
- Farmers can only exchange one plot per year; for example they try to give away a plot when they have many others which are more worthwhile for them to exploit or when they do not have enough money or family labour. They try to get a plot when they have a lot of money and/or many family workers and when they own a well capable of irrigating the neighbour's plot intensively.
- The market price is neither influenced by production, nor is production influenced by the market price, which remains fixed during simulation except for market gardening.
- All plots and farmers obtain the same yield, except in the cases of dry farming, which largely depends on rain and market gardening which is influenced by phyto-climatic and economic variation and varies according to a random factor in the model.

The climate is represented by the monthly pluviometric data collected in the region during the last 20 years, and this series is repeated for as long as the model runs. This representation of the climate does not seek to be very realistic and does not take extreme situations such as drought years into account. It nevertheless enables us to avoid adding random factors, which simplifies exploration of the relationships between the different components of the system. Nevertheless, extreme climates were simulated for the model validation, along with other extreme conditions. The most appropriate time scale to represent the dynamics of the system was the year, the drop in the water table depending mainly on seasonal rotations and on inter-annual investment. So the basic time step of the SINUSE model is the year divided into two cropping seasons. At the beginning of the year, farmers check their situation and may possibly send messages to their neighbours to temporarily exchange plots. They then seasonally exploit their plots and they may take the plot for the year. At the end of each season, the water demand of the irrigated plots, taking irrigation efficiency into account, is summed up for each water table zone. There may be a drop in the water table, depending on its hydrogeological parameters. The resulting level difference between the water table zones can lead to water exchange that in turn modifies the piezometric level. At the end of the year, farmers assess their situation and compare it to their objective. On the basis of this assessment, they may decide to invest in a well or in a plot, to sell a plot, or wait until they can make a better decision. They cannot afford more than one investment for each time step.

Questions regarding interaction with the market or the inheritance of plots were not dealt with in this model, hence limiting the meaningfulness of simulations over long time spans, i.e. above 30 years or so. It is therefore preferable to limit the number of time paths to 30 for one simulation.

3.3. The entities of the model

The SINUSE model involves three kinds of entity, which constitute classes in object language:

- *social entities*: the farmers, who are able to send messages;
- *spatial entities*: the plots, the PPIs and the water table

[2] The Cormas platform is downloadable at: http://cormas.cirad.fr. To obtain SINUSE model contact the corresponding author.

zones, which are aggregates of cells, their form and area varying from one to another;
- *located entities*: the wells and boreholes.

They are described using the unified modelling language (UML) method (Muller, 1998) in Fig. 1. Each plot instance is attributed to a farmer instance, which has one or several plots. The data collected in the field showed that the farmers' objectives were very similar, depending above all on their situation. As a consequence, in spite of the observed diversity, we chose to represent the farmers as a single group, with each agent acting according to the combination of its own parameters, rather than as different groups of computer agents each characterised by a specific set of objectives, parameters and rules. The water table is roughly represented by two zones characterised by their hydrogeological parameters and is able to exchange water between each other, each being divided into several sub-zones characterised by their water depth. Each class can be seen as the basis of a distributed information in terms of space, time and activities, and is able to interact with the other classes according to its own rules (Fig. 2), as if it were a kind of simplified but dynamic geospatial intelligence system (GISs).

Different kinds of interaction between farmers are implemented (Table 1), concerning the construction of wells and land exchanges. Fig. 3 shows an example of an implemented procedure belonging to the farmer class 'buildAWell', in UML language. When this procedure is called, the farmer checks his plots and tries to group them in order to obtain an area large enough to build a borehole (at least 20 ha) or a well (at least 4 ha). To build a borehole, at an estimated average cost of 50,000 DT (Tunisian dinars), the farmer must have at least 80% of this amount, assuming that he can easily borrow the other 20% through private or family loans. This type of favourable situation is rather rare. More frequently, farmers are able to build a well in a worthwhile place, which means that not only they must own the minimum area required for this investment, but it must be located in a risk-free place, where other functioning wells already exist and the farmers need to have at least 65% of the amount of money required. Other procedures are implemented to build a well; one for those who already own a well, one for those who display high-risk behaviour, one for those who try to team up with a neighbour and one for those who try to build a well alone on a small plot.

The dynamics of a time step involves a sequence of procedures followed by the different objects of the system (Fig. 4); it can be visualised through several time steps by means of a spatial grid that represents the investigated zone (Fig. 5). This grid is composed of 2400 cells, each one representing 1 ha. It thus covers approximately 10% of the investigated area, the other factors of the model following the same scale reduction.

The dynamics of the modelled system can also be analysed through a representative selection of indicators describing different entities of the model, according to the main objectives of the model.

- Changes in the water resource are analysed via the global piezometric level of the water table.
- The total number of wells is studied to provide intermediate information about the farmers' behaviour and its impact on the system dynamics.
- The socio-economic situation of the farmers are analysed through the annual number of farmers who are not in debt, or through the global agricultural income.

As Table 2 shows, several parameters of the model are randomised, introducing chance in the initialisation process and during the simulation. Simulations for one scenario must therefore be repeated several times and simulation results are interpreted by comparing several scenarios.

The comparison of two scenarios is based on the non-parametric Wilcoxon–Man–Whitney test that gives conclusions about the difference between two samples, according to a chosen significance rate. The comparison of 20 repetitions of the same scenario was tested on many scenarios, which led to the conclusion that this number of repetitions is sufficient in that case to evaluate the variability of results. As the results of these simulations must be analysed in terms of comparison, we chose to systematically represent the outputs of the 20 repetitions rather than as a mean and a standard deviation, that do not allow us to check the variability of a given path.

3.4. Results

Fig. 6 shows several indicators used to follow the dynamics of a status-quo scenario over 80 years. This long period was chosen to evaluate the stability of the model over the long-term and to locate possible faults. As these graphs show, the modelled system evolved as follows over the long-term:

- The total number of functioning wells of the system first grows—at a rate approximately the same as the actual rate observed over the past few years—then stabilises (due to a lack of space or money to build new wells) and finally decreases, as the water table is generally too deep for the wells to function, given the current technical constraints.
- Initially, the water table drops in a linear manner, though it later starts to level off. This can be explained by the last indicator, as the number of wells decreases, the extracted volume decreases likewise.
- In fact, the volume extracted for irrigation follows regular and periodic variations due to the climate

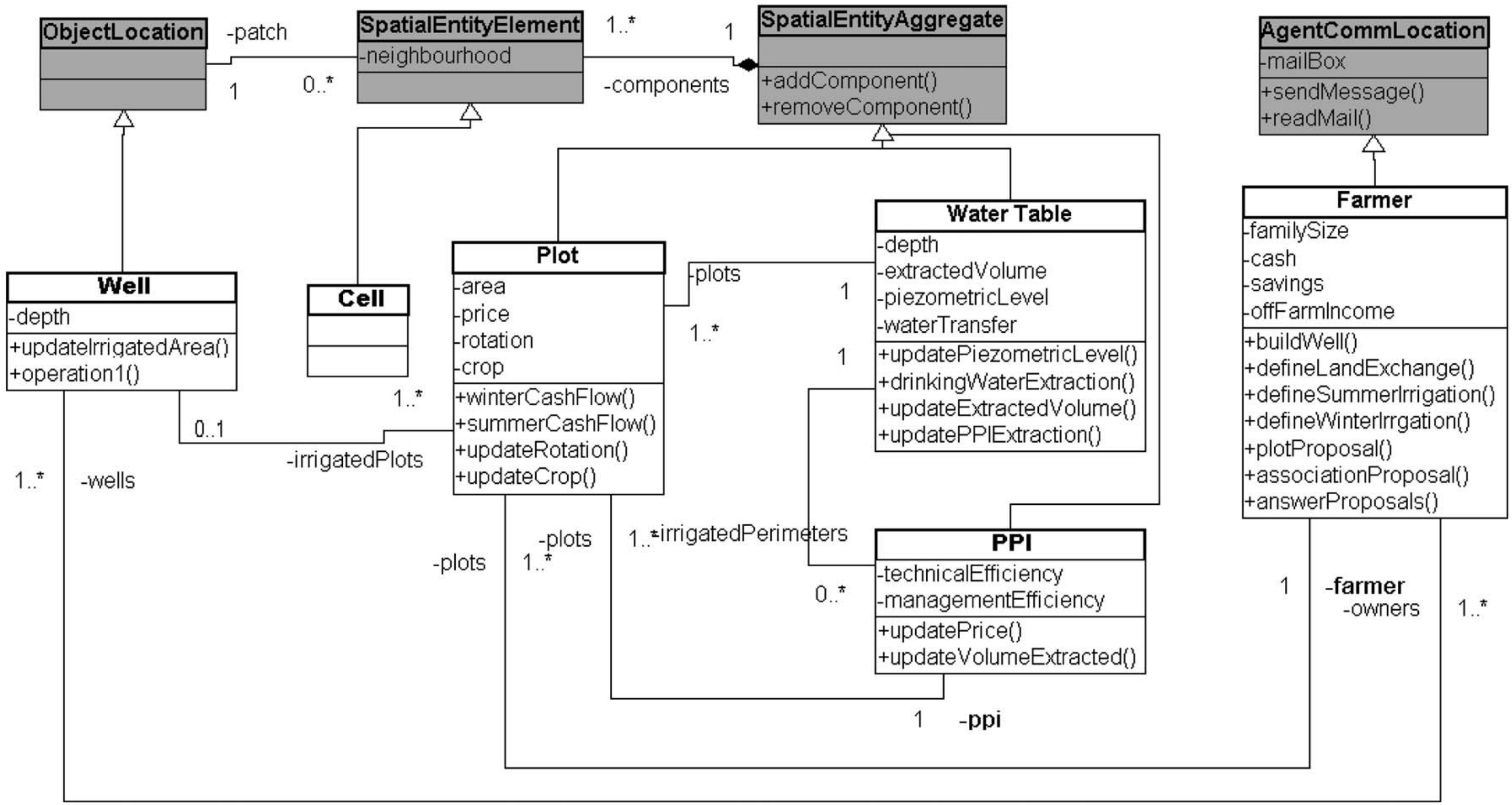

Fig. 1. The SINUSE model comprises five main types of entity, also called classes, that inherit from four types of Cormas entity, figured by the upper classes in grey.

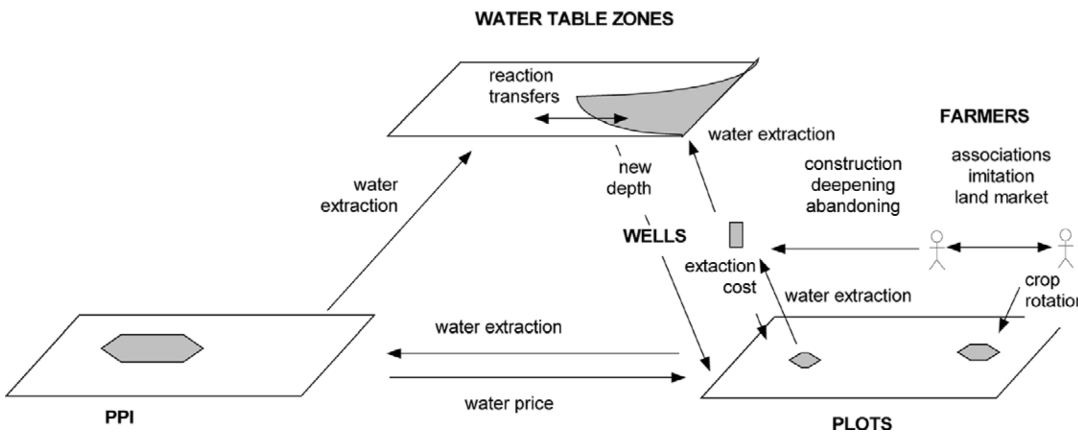

Fig. 2. The entities of the SINUSE model interact with each other during a time path.

Table 1
Different kinds of interaction between farmers in the SINUSE model

Type of interaction	Object	Range
Involving message exchanges		
Temporary land exchanges	Exchanging plots	Neighbourhood 2 or 3
Teaming up to build a well	Well construction	Neighbourhood 1
Well construction on an exchanged plot	Well and plot	Large neighbourhood
Land market	Plot	Neighbourhood 2
Without message exchanges		
Well construction on small plots in view of poor land exchange prospects	Well	Neighbourhood 2
Imitation	Well	Neighbourhood 2
Abandoned wells in the neighbourhood	Well	Neighbourhood 3
Neighbourhood impact on the price of the plot	Land price	Neighbourhood 2

The neighbours here correspond to the plots that are located next to the considered plot, on a spatial grid: for instance neighbourhood 1 refers to the plots which are located right next to the considered plot; neighbourhood 2, both to the direct and to the secondary neighbours of the considered plot.

(represented by a 20-year sequence of data) and the wells extract far more water than the PPI. Generally speaking, the volume extracted tends to grow, to stabilise, then to decrease, as explained above.

- The total annual farmers' income seems to fluctuate in an irregular manner, though a scenario without randomisation of market gardening production indicates that these irregular variations are mainly due to the randomised production of market gardening, and that apart from this chance mechanism, income logically follows the same tendency as the volume extracted and the number of wells: an increase, followed by stability and a final decrease, while the regular variations follow the climatic variations.

This kind of experiment shows that, depending on the choice of indicators, the model follows logical and realistic tendencies; in the early stages of the simulations, which represent the near future, it faithfully reproduces the dynamics observed on the field during the past few years. But this is not sufficient to draw a conclusion regarding its credibility.

3.5. The credibility of the model

The difference between strong validation and establishing credibility is that, in the first case, the model is perceived as an exact representation of reality and can thus be used for predictions while in the second case—often the case for complex systems—the aim is to understand the properties of interacting processes. But many existing processes are designed for both validation and accreditation. Verification and validation are two different tasks within the modelling process.

Verification is determining that a computer simulation program is a fair representation of the conceptual model

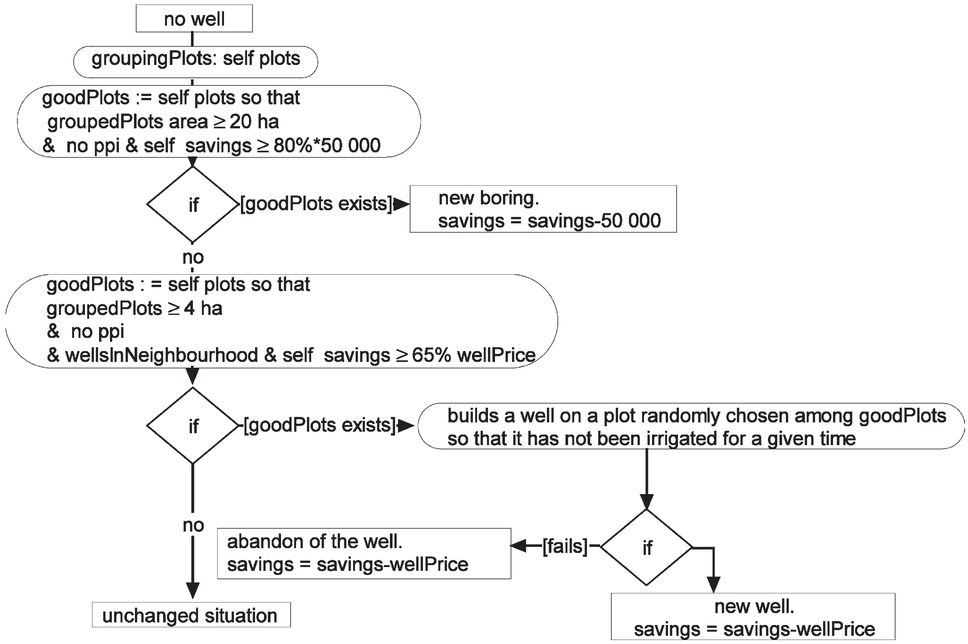

Fig. 3. 'Build a well': a procedure of the farmer class to allow the agent to build a well under given conditions, described in UML.

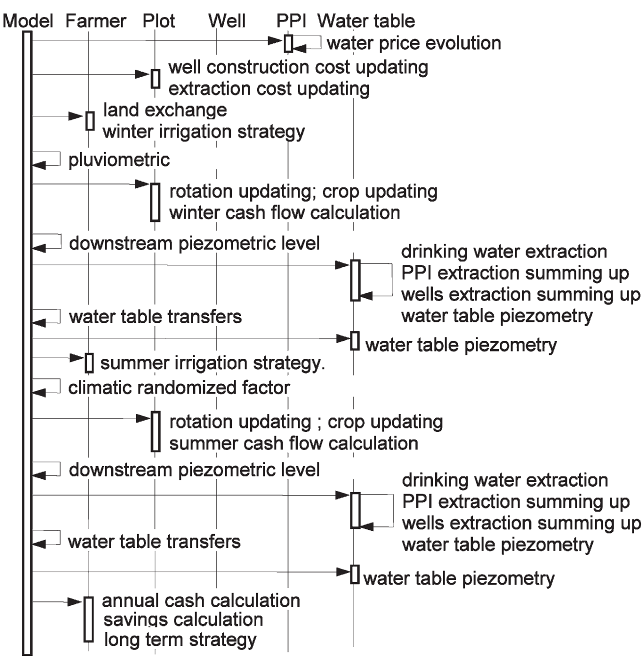

Fig. 4. The simplified sequence diagram of the SINUSE model in UML shows the sequence of different procedures run during a time path. A vertical line represents each class. The class instance activation is represented by a rectangle on this line. Objects communicate by exchanging messages that are represented by horizontal arrows pointing from the sender to the receiver of the message.

while validation is determining whether both the conceptual simulation model and its implementation are an accurate representation of the model under study. Verification essentially consists of checking if the model output is reasonable and debugging the conceptual model and the computer program. The SINUSE model verification was essentially based on two steps: verification of the conceptual model by means of UML schemes and program debugging through the use of an interactive debugger able to stop the simulation in the event of incoherence.

The classical tests for model validation recommended in the literature are comparison of the model output with reality or with other models, behaviour of the model in extreme situations, sensitivity tests on the parameters, tracing of specific variables during simulations, etc. (Lewis, 1993; Rykiel, 1996). Whereas these tests are often used to validate classical models, there is no widely accepted methodology for validating a complex model (Brown and Kulasiri, 1996). The SINUSE model involves 50 parameters, of which approximately 10 are randomised, and so cannot be totally explored. There are some references to experimental design for validation of simulations (Kleijnen, 1998). Bart (1995) suggests testing only important parameters, one by one, while Barreteau (1998) and Barreteau and Bousquet (2000) chose to study the validity of his model by means of 100 scenarios based on the randomised choice of a set of parameters values, and to simulate each scenario 20 times, in order to take the dynamics variability into account.

We chose the following approach.

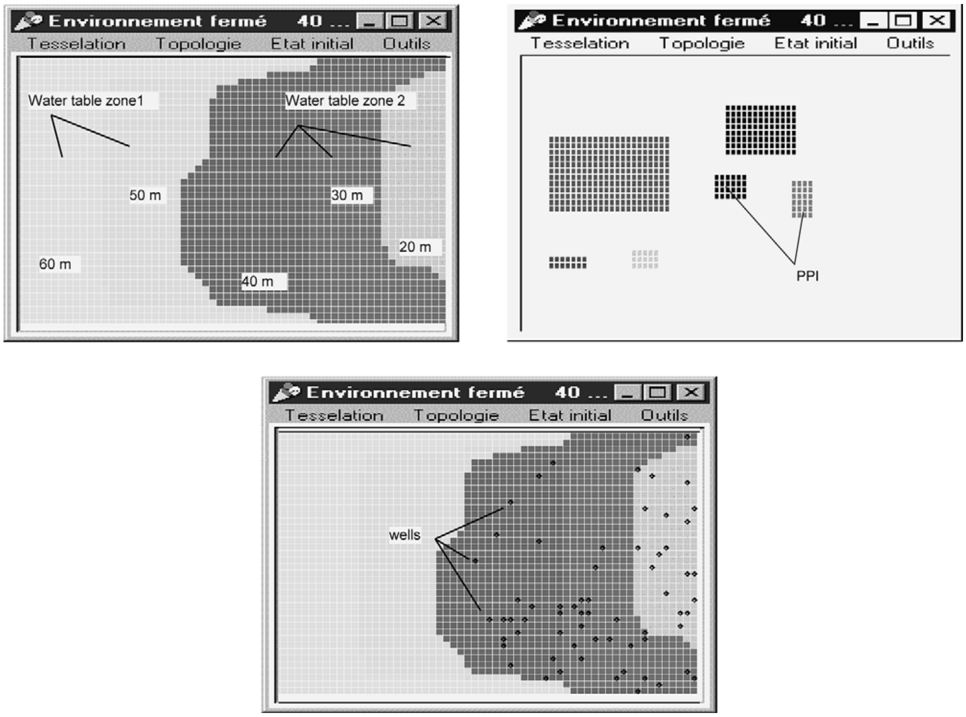

Fig. 5. Several points of view given by the SINUSE model spatial grid: the water table zones and sub-zones with its initial depth, the wells at a given time step and the PPI.

Table 2
The randomised factors of the SINUSE model

Randomised factors used to initialise the model	Randomised factors used during simulation
Plot distribution in space and in area classes	Savings, risk of depreciation
Constitution of farms and distribution of plots to farmers	Summer market gardening production
Initial well distribution in space and to farmers	Temporary diversification of income
Farmers' family structure	Plot choice for the construction of wells
Outside income distribution to the families	Plot choice for the land market
Initial savings distribution to farmers	Plot choice for farmers' teaming up to build a well
	Risk of abandoning well during construction or deepening
	Individual risk aversion

In most of the cases, these factors are not completely randomised: for example the distribution of initial savings to the farms depends on the size and equipment level of the farm.

- First, in line with Rykiel, we determined whether the simulation outputs were reasonable. Analysis of the model running under a variety of input parameter settings allowed us to check that the outputs were reasonable, in comparison with the studied system dynamics. Analysis of model variability and stability over the long-term—performed over an 80-year period—and extreme tests revealed that the SINUSE model is robust and reacts correctly to various extreme scenarios (like very high incomes, no risk aversion, very high probability of abandoning a well, rainy and dry climates). Generally speaking, the results of these tests were very satisfactory (Feuillette, 2001). The tracing of several agents during the simulations, on the basis of six parameters (farm area, number of plots, cash, savings, wells, PPI) also enabled us to check the coherence of a simulation and in the light of the other test results, to conclude that the individual behaviour of the different agents lead mainly to realistic global tendencies.
- Second, we chose to follow Law and Kelton (1991) who recommend studying the main effects and the crossed effects of aggregated factors by grouping several parameters of the same kind and identifying

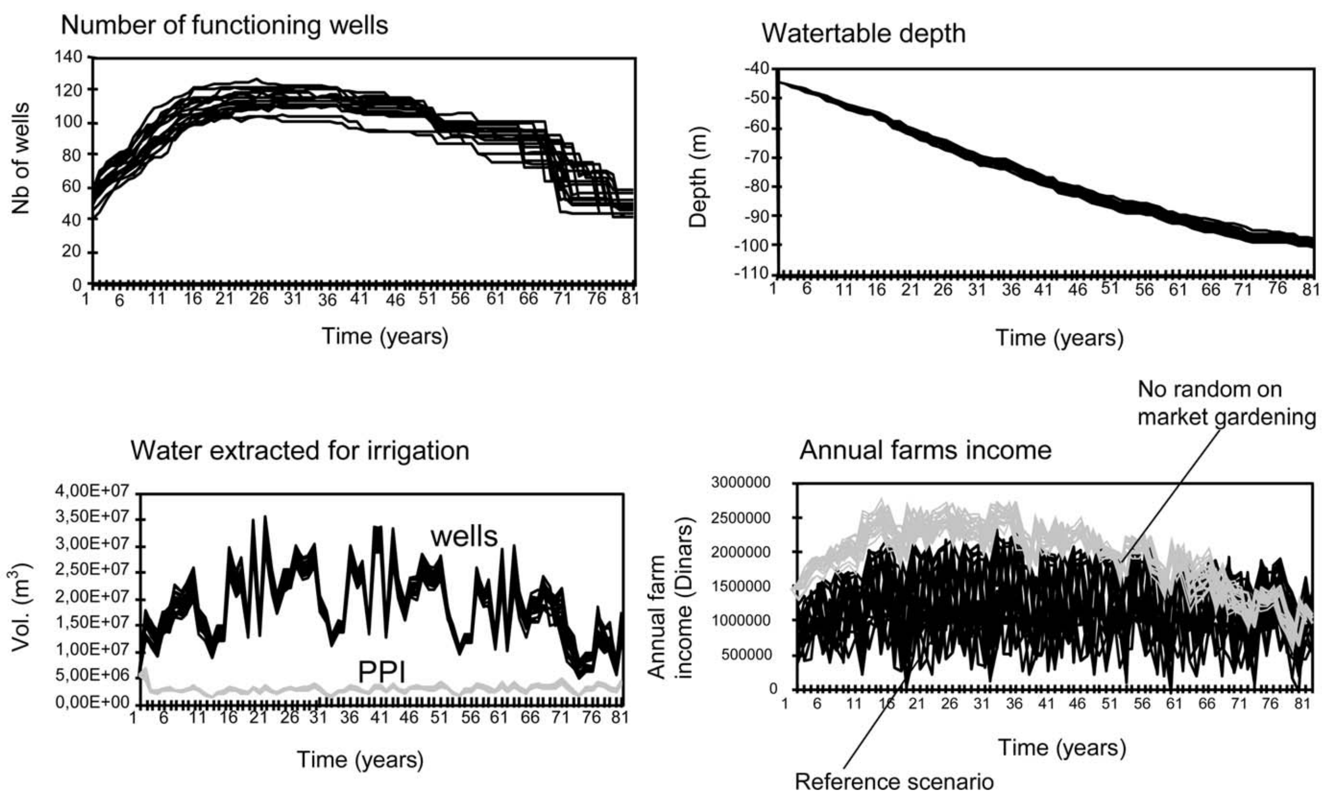

Fig. 6. Twenty repetitions of a reference scenario run over the long-term (80 years) and analysed through four indicators, show the stability of the modelled system and its evolution. Each curve of the same colour represents a simulation of the same scenario.

important parameters recursively, when a factor seems important. We performed a partial sensitivity analysis based on 18 parameters grouped into four factors (economic, social, technical and environmental) to evaluate the reaction of the modelled system for a low or high value of each factor. If major sensitivity to a factor is identified, then the sensitivity of each of its parameters are tested (Feuillette, 2001). The sensitivity analysis notably included testing of the main model hypothesis. For instance, Fig. 7 shows how the modelled system reacts to the elimination of local interactions such as imitation, through two selected indicators. These simulations confirm the main hypothesis of the model; some local interactions do have a major impact on the global dynamics of the modelled system.

On the other hand, the experiments showed that the model fails to represent certain socio-economic mechanisms correctly. Indeed, crossed experiments on the model such as individual tracing showed that the socio-economic behaviour of the farmer agents, based mainly on assumptions, leads to unrealistic situations where the poor farmers become too heavily in debt and the rich ones get too much money. This leads to excessive activity in the land market, with more than 3/4 of the farmers having sold the totality of their plots within 10 years. In reality, fewer than 5% of the farmers surveyed in the field have reported selling one of their plots, and none of the farmers surveyed own land today. This distortion interestingly reveals that further research on the farmers' strategy of income utilisation should be conducted and that simulated behaviour should be validated by the stakeholders. Furthermore, the validation experiments revealed that some of the parameters tested, such as hydrogeological ones for example, appeared to have a significant impact on the model and should therefore be understood better. Still, the conclusion of the experimental plan is that generally speaking, the SINUSE model can be used to explore the dynamics of the studied system. It appears to be sufficiently realistic, coherent and robust to fulfil its goals, i.e. to raise important questions about system management, provided that the limits of the model are well known. We could therefore use it to test management scenarios.

4. Use of the model

This model has been developed for use as a research or experimental tool, to explore the dynamics of the system and to test scenarios. Indeed, the simulations

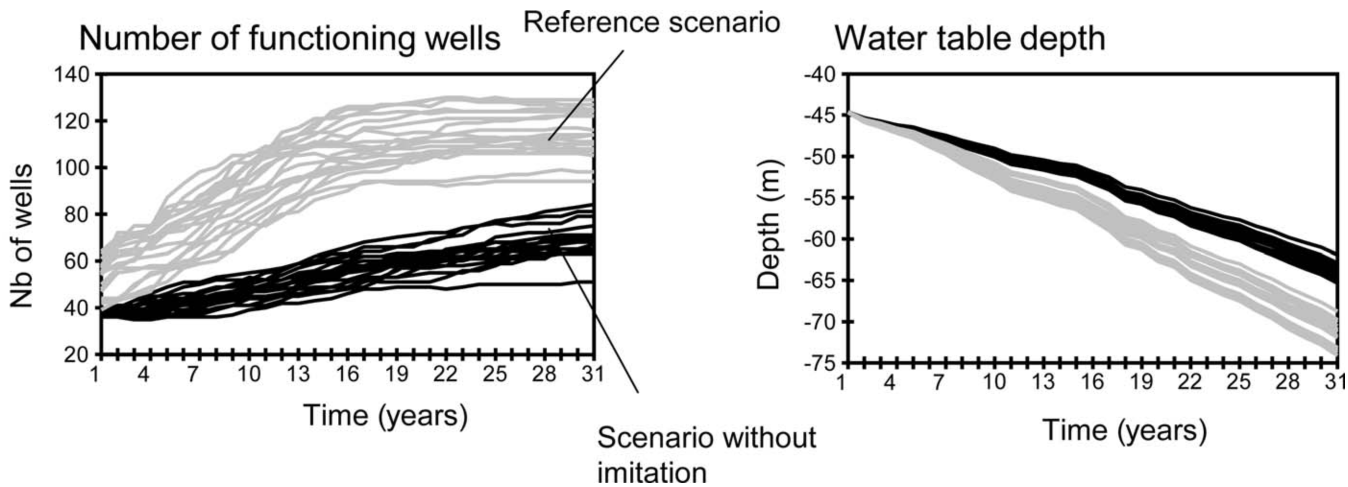

Fig. 7. A simulation without imitation is compared to the reference scenario.

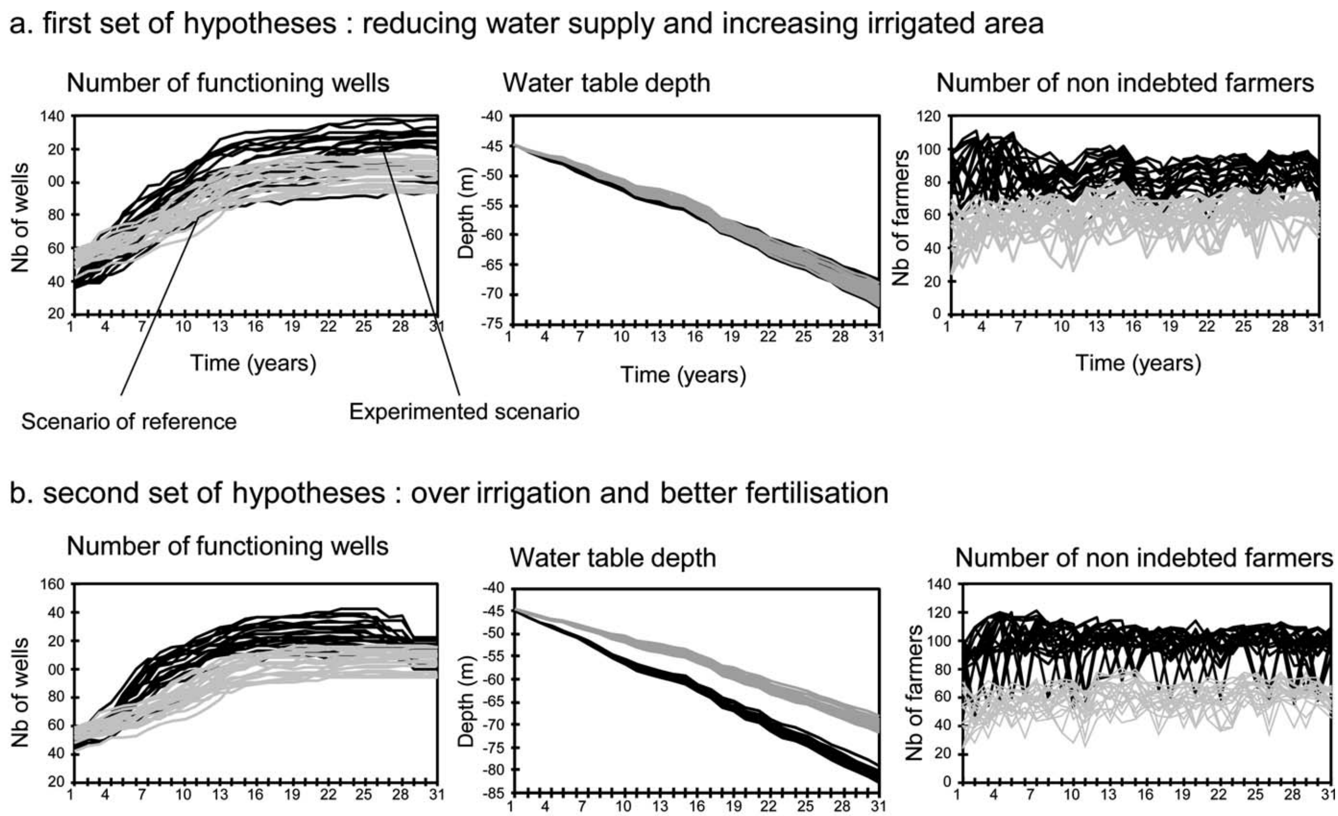

Fig. 8. Simulation of the introduction of dropping equipment for irrigation, as compared to the reference scenario, shows that the system's reaction can be surprisingly contrary to expectation.

presented above constitute a first step in the exploration of the system, as they reveal the importance of the parameters tested and raise questions about how the system evolves in certain situations. As a second step, the SINUSE model can be used to simulate management interventions (Feuillette et al., 2000a), or changes in the rules or in the behaviour of the actors. As an example, Fig. 8 presents the results of the simulation representing the generalisation of efficient dropping irrigation equipment. Generally speaking, improving water use efficiency is considered to have major potential for meeting future food production requirements and is therefore highly recommended, above all in arid or semi-arid zones (Wallace, 2000). This experiment is all the more interesting as it represents a current intervention in the field: the Tunisian authorities are currently subsidising the installation of dropping equipment in farms, to improve irrigation efficiency and hence the economic results for farmers, and to limit the volumes extracted in order to preserve the resource. We chose to simulate two different sets of hypotheses. The first is inspired by an experiment conducted in another part of the country, where the introduction of dropping equipment has led to over-irrigation and better fertilisation. The second comes from our field observations: when a farmer invests in more efficient equipment and is therefore able to extract more water, he tends to extend his irrigated area, within the limits of his possibilities, of course. The comparison of these scenarios with the reference one shows that in the first case (Fig. 8(a)), the dynamics of the system lead to a worse situation in terms of resource sustainability, the results of the farmers being so greatly enhanced that they invest more, whereas in the second case (Fig. 8(b)), the results concerning the resource are not very different (though there is a minor statistical difference), and the farmers' results improve.

5. Discussion and conclusion

As we have seen earlier, though some of the socio-economic procedures of the modelled agents of the SINUSE model are based on observed behaviour of the farmers, most of them rely on assumptions, as questions about the farmer's behaviour appeared during the modelling phase, i.e. far from the field. In fact, our experiments have shown that certain mechanisms, such as land exchanges, are highly unrealistic and this probably disturbs the global dynamics of the system. To resolve this problem, a return to the field is necessary to verify the assumptions on socio-economic procedures by means of inquiries and to 'socially validate' (Barreteau and Bousquet, 1999; Barreteau et al., 2001) all the behaviours implemented by the actors.

This work nevertheless enabled us to improve our knowledge of the system, as it raised questions about the determining factors of water demand and the farmers' behaviour, and it proved that MAS are useful tools to model complex, distributed systems (Feuillette et al., 2000b). SINUSE can be considered as a first step in the use of MAS for groundwater studies, and it has proved the relevance of taking local and non-economic interaction into account in the case of the Kairouan water table. Although SINUSE was designed from specific field research and can therefore be considered as over-specific, the approach described above can be transferred to other contexts of the same order. Due to its transparency and capacity to simulate many different scenarios, it can be a useful tool for negotiation.

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