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AGENT-BASED MODELLING AND SIMULATION IN THE IRRIGATION MANAGEMENT SECTOR: APPLICATIONS AND POTENTIAL

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SUMMARY - In the field of sustainable development, the management of common-pool resources is an issue of major importance. Several models that attempt to address the problem can be found in the literature, especially in the case of irrigation management. In fact, the latter task represents a great challenge for researchers and decision makers, as it has to cope with various water-related activities and conflicting user perspectives within a specified geographic area.
Simulation models, and particularly Agent-Based Modelling and Simulation (ABMS), can facilitate overcoming these limitations: their inherent ability of integrating ecological and socio-economic dimensions, allows their effective use as tools for evaluating the possible effects of different management plans, as well as for communicating with stakeholders. This great potential has already been recognized in the irrigation management sector, where a great number of test cases have already adopted the modelling paradigm of multi-agent simulation.
Our current study of agent-based models for irrigation management draws some interesting conclusions, regarding the geographic and representation scale of the reviewed models, as well as the degree of stakeholder involvement in the various development phases. Overall, we argue that ABMS tools have a great potential in representing dynamic processes in integrated assessment tools for irrigation management. Such tools, when effectively capturing social interactions and coupling them with environmental and economical models, can promote active involvement of interested parties and produce sustainable and approvable solutions to irrigation management problems.

Key Words: agent, agent-based modelling, simulation, irrigation management, stakeholder participation

RESUME *- Dans le domaine du développement durable, la gestion des ressources communes est une issue d'importance majeure. Plusieurs modèles visant à adresser le problème existent en littérature, en particulier dans le cas de la gestion d'irrigation. En effet, celle-ci représente un grand défi pour les chercheurs et les décideurs, car elle doit prendre en compte les différentes activités liees à la gestion de l'eau et les diverses, souvent conflictuelles, perspectives des usagers de l'eau dans un secteur géographique spécifique.*
Les modèles de simulation, et en particulier la modélisation par simulation multi-agents (MSMA), peuvent faciliter l'approche à la résolutions de ces limites: leur capacité spécifique d'intégrer les dimensions écologiques et socio-économiques, permet leur utilisation comme outils efficace pour l'évaluation des possibles impacts de différents plans de gestion, aussi bien que pour communiquer avec des parties prenantes. Ce grand potentiel a été déjà identifié dans le secteur de la gestion de l'irrigation, où un grand nombre de cas étude ont déjà adopté le paradigme de la modélisation par simulation multi-agents.
Notre étude courante des modèles multi-agents pour la gestion de l'irrigation mène à quelques conclusions intéressantes, concernant les échelles géographique et de représentation des modèles passés en revue, aussi bien que le degré de participation des intervenants dans les diverses phases de développement. De façon générale, nous soutenons que les outils de MSMA ont un grand potentiel pour ce qui concerne la représentation des processus dynamiques dans le cadre d'outils intègres d'évaluation pour la gestion de l'irrigation. De tels outils, en capturant efficacement des interactions sociales et en les couplant avec les modéles environnementaux et économiques, peuvent favoriser la participation active des parties concernées et produire les solutions durables et appropriées aux problèmes de gestion d l'irrigation.

Mots clés*: agent, modélisation multi-agents, simulation, gestion de l'irrigation, participation des parties prenantes*

INTRODUCTION

In the field of sustainable development, the management of common-pool resources is an issue of major importance. Several kinds of models that attempt to address the problem can be found in the literature, especially in the case of water management. These models may be approximately categorized as follows (Bousquet et al., 1999):

(i) *physical models* focusing mainly on the dynamics of resources and restricting social dynamics to resource exploitation;
(ii) *agro-economic models* attempting to manage a fixed amount of resource within a framework of competitive exploitation; and
(iii) *combinatorial models*, which integrate the ecological and socio-economic dimensions of common-pool resources management in terms of their dynamics and interactions.

The latter approach reflects the current trend, since scientists working in the field have already recognised the need to examine the interaction between ecological and social dynamics and to "couple the environmental models to the social systems that are embedded in them" (Hare and Deadman, 2004). A scientific paradigm that drives towards this direction, is Agent-Based Modelling and Simulation (ABMS).

Agent-based modelling (ABM)

Before looking into Agent-Based Modelling and Simulation techniques (that we will refer to with the acronym ABMS), we need to define the terms *agent* and *Multi-Agent System* (MAS).

The term *agent* (Wooldridge and Jennings, 1995) is used to denote a hardware or software system that: (i) operates without the direct intervention of others and has some kind of control over its actions and internal state (*autonomy*); (ii) interacts with other agents using an agent-communication language (*social ability*); (iii) perceives its environment and responds to changes that occur in it (*reactivity*); and is able to exhibit goal-directed behaviour (*proactivity*). It is important to distinguish between this definition and the attribution of the term agent to human actors in the context of participatory procedures, as our study will focus mainly on software agents. However, it is worthy to underline that in both cases an "agent" is considered to be attributed the same characteristics, namely autonomy, social ability and proactivity.

Multi-Agent Systems comprise multiple agents, which interact among themselves or with objects in their environment. MAS usually display the following characteristics: (i) each agent has its own perception of its environment (in terms of access to information or problem solving capabilities this usually implies that each agent has a limited viewpoint); (ii) there is no system global control; (iii) data are decentralized; and (iv) computation is asynchronous. Due to their distributed nature, MAS provide effective solutions to problems that can naturally be regarded as a "society" of autonomous interacting components. Similarly, they can be used in situations where expertise is spatially or temporally distributed, in solving complex, large or interdisciplinary problems (Sycara, 1998).

Building on the above definitions that have their roots in artificial intelligence, distributed computing and software engineering, ABMS tries to represent complex systems by defining individual entities (agents) and formulating the methods that correspond to their behaviour in the specific environment. In that respect, ABMS "takes a bottom-up approach to generating data comparable to that observable in the real world system analysed" (Deadman, 1999). The overall behaviour of the system is not explicitly specified; instead it emerges as a result of the actions and interactions of the individual agents within the MAS.

Participatory processes in renewable resource management

Integrated Assessment (IA) has emerged as an efficient method for tackling complex environmental problems like the modelling of renewable natural resources. It involves an interdisciplinary process of combining and communicating knowledge from different scientific domains to achieve a better understanding of complex phenomena. In this context, it is of paramount importance to develop appropriate means for representing the human dimension in integrated models, and thus produce more sustainable and enduring resource management strategies.

Participatory methods are used in a growing fashion to capture the behaviour of representative actors and to realistically incorporate their perspectives in the design of the models. In this direction, ABMS presents particularly promising features to be integrated with participatory processes, as (i) it permits the integrated study of resource management issues taking into account both ecological, environmental, social and economic factors; and (ii) can model the adaptive human decision making mechanisms, as well as the complex interaction processes between the actors involved. Furthermore, ABM is a method producing models that are descriptive and straightforward, thus promoting the active involvement of stakeholders and domain experts in model development.

Thus, it is evident that the combination of ABM with participatory methods may lead to more effective model construction, through a process of developing a shared problem perception between the modellers and the different stakeholders involved (Pahl-Wostl, 2002). Hopefully, this will yield a richer base for policy-making than the use of traditional modelling approaches and can upgrade decision making to a process of social learning.

Methodology

This paper aims at providing an overview of agent-based models used in water resource management in the irrigation management sector. The following section describes a selection of representative test cases, in terms of their objectives, modelling approach and assessment. Next, we introduce two classification schemes for the presented agent-based models, in order to categorize them according to their (i) scale; and (ii) degree of stakeholder involvement. These classification schemes and their corresponding tables aim to assist the interested researcher and practitioner to compare the features of existing models and better assess their utility and applicability to the problem at hand. We conclude with some insights on ABM potential and constraints, while issues concerning the penetration of ABM in the water management sector and future research directions are also addressed.

AGENT-BASED MODELS FOR THE MANAGEMENT OF IRRIGATED ECOSYSTEMS

Managing an irrigated system is a complex task, having to cope with various water-related activities and conflicting user perspectives within a specified geographical area – basin, catchment, watershed etc. Typically, there are several stakeholders involved, and their different, typically contradictory goals must be seriously taken into account during the management procedure. Water supply for domestic, agricultural or industrial use, environmental issues and even recreation provision are only some of the activities the different stakeholders may engage in. Moreover, overexploitation of the resource often leads to water scarcity, aggravating the situation to a socio-economic power struggle. In such complex and multidimensional cases, management strategies not only have to balance water demand and supply, but also devise solutions that meet the approval of all users. Issues like the prioritisation of users, the construction of water tariffs, the protection of ecological reserves, the compliance with the economic objectives and the legislative context, are all to be equally considered. Further, this is to be done within a system of strongly coupled biophysical, social and economic entities, where the impact of certain strategies cannot be assessed by long-term studies or experimental manipulations alone.

Simulation models, and particularly agent-based simulation models, are tools that can facilitate overcoming these limitations. Such tools can be used to evaluate the possible effects of different management plans, as well as to communicate with the stakeholders, as they can effectively consider the social dimension. Various test cases have adopted ABMS for irrigation management, which are summarized below. These models may be concerned with the problem in different geographical scales, but all share the common modelling paradigm of multi-agent simulation.

The sections that follow provide a brief overview of the related literature. For each reviewed model the presentation includes the objectives, the modelling approach and our own critical assessment.

SHADOC

Objective

SHADOC (Barreteau and Bousquet, 2000) is a MAS seeking to examine the viability of, currently underutilized, irrigated systems in the Senegal River Valley. Based on the assumption that the interaction of the different system components has a large impact on its viability, the model focuses on rules used for credit assignment, water allocation and cropping season assessment, as well as on organization and coordination of farmers. The main interest is in the investigation of how existing social networks affect the viability of irrigated systems.

In a later attempt (Bousquet et al., 2002), the authors of SHADOC propose the combined use of MAS and Role Playing Games (RPG) as a new methodology named *companion modelling*. They argue that RPG can be used "both to elicit knowledge and to simulate it in a less controlled way", thus promoting a better understanding and modelling of decision making processes in the area of renewable resources management. To support this approach, a series of six tests was conducted, among which there is one concerning the viability of irrigation schemes in Senegal: a role game was designed for SHADOC to be presented to the various stakeholders.

Modelling approach

The *companion modelling* methodology involves the following stages:

(i) Construction of an artificial world, using the MAS modelling methodology. This presupposes that the different stakeholders have been clearly identified and their perceptions have been defined.
(ii) Validation of the knowledge represented in the model, through an RPG, where stakeholders play roles corresponding to the agents, while taking into account the representation and communication constraints of the model.
(iii) Simulation phase, divided in two sub-phases:
    a. a role play to validate the model and identify scenarios of interest
    b. the MAS simulations based on the aforementioned scenarios.

Particularly for the case of irrigation management in the Senegal River valley, the first step was the implementation of a MAS model called SHADOC. The modelling of the system is limited to a single irrigation scheme, which is represented as a place of acquisition and distribution of two resources: water and credit. The societal model is structured with three types of *group agents*, each of which corresponds to a group of people in charge of credit management, watercourse and principal network management or pumping station management. As far as *individual agents* (farmers) are concerned, the model employs a four-level social categorization with (i) farmers who wish to obtain an income from their plot; (ii) farmers who want to earn the food their family needs; (iii) farmers who simply want to keep their plot; and (iv) circumstantial workers, waiting for a better job opportunity.

Finally, there is the notion of "friendship network", which defines the group of people a farmer may collect information from and also considers worthwhile to compare himself to. This friendship network acts as a pool of behaviors a farmer may imitate, if his previous strategy proves inefficient during the assessment stage.

According to the companion modelling methodology, the second step was to present the model to the stakeholders, in order to validate it and test its potential as a negotiation support tool. For this purpose, an RPG was designed whose structure strongly resembles that of the MAS model. The game is played with 10 to 15 players, representing farmers, and cards are used to define possible behaviours, in terms of the farmers' aim of planting, their social status and their propensity to repay loans. For the representation of the irrigation scheme, a board is used to attribute plots to the players, and keep record of the amount of water used and the choices made at the time of planting. Finally, seasons are subdivided, into three successive phases: (i) obtaining credit; (ii) irrigation operations; at the end of which potential yields are calculated; and (iii) evaluation, after which players may change cards if they wish.

The role game was initially tested in the villages where the field survey was conducted and, a year later, it was presented to farmer associations and technical staff at a workshop organized in Senegal. In both cases, the tool was warmly welcomed and proved to be an effective way to help the participants understand the model and its relation with reality. Furthermore, having played the RPG, participants realized the simplifications of the MAS model and gained insights on how simulation results should be interpreted.

Assessment

From the summary presented above, it is evident that SHADOC takes an approach based both on individual (farmer agents) and collective enforced rules (group agents). Moreover, the variation of behaviours on all levels from individual behaviour and collective rules to the patterns of interaction between farmers emphasizes the diversity of behaviours and allows for the exanimation of multiple scenarios of rules enforced to an irrigated system. The practical application of the system is, though, restricted by the fact that its hydraulic and agronomic modules have been drastically simplified during the modelling phase.

On the other hand, the companion modelling methodology is an interesting attempt to validate a MAS model through play. The RPG, played with representatives of all levels represented in the system, can provide useful feedback on the behaviours modelled, together with the interactions processes between the various actors. Furthermore, switching roles between actors promotes mutual understanding and prepares the ground for a constructive discussion. As the aim of the approach is not prediction but negotiation support, its greatest value lies in the fact that it combines simulations and role games to identify and formalise problems for discussion, leading to real negotiations.

SINUSE

Objective

SINUSE (Feuillette et al., 2003) addresses the problem of integrated management of the Kairouan water table, located in Tunisia, which has been continuously decreasing for more than 20 years. It is an attempt to model the observed system dynamics and explore the effects of different kinds of intervention.

Modelling approach

The main hypothesis of the model is that local interactions among users and between users and the resource do have major impacts on overall lowering of the water table. Based on this, the SINUSE model involves three kinds of entities:

(i) *social entities*: farmers, who are able of exchanging messages
(ii) *spatial entities*: the plots, the public irrigated perimeters, and the water table
(iii) *located entities*: the wells and boreholes.

The farmers are represented as a single group with the same objectives and rules. Within this group, differentiation in farmers' behaviour is only due to their individual parameters. Moreover, farmers are able to communicate with each other within a specified neighbourhood, depending on the communication objective – land exchange or well construction. A non-communicative procedure of 'imitation' is employed by farmers when they are seeking worthwhile plots to build a well, as it is safer to do so when there is already a well in a neighboring plot.

During a simulation, the dynamics of the system can be visualized by means of a spatial grid that represents the investigated zone. A set of indicators, corresponding to the model objectives, is also available. This set includes the piezometric level of the water table, the total number of wells, the annual number of farmers who are not in debt and the global agricultural income.

Assessment

SINUSE has been developed for use as a research tool to explore the dynamics of the system and test scenarios theoretically. It was subjected to a thorough validation procedure to ensure that simulation results are reasonable and to evaluate the model's reaction to various parameters grouped into four factors: economic, social, technical and environmental. Although some experiments showed that the model fails to represent certain socio-economic mechanisms correctly, it can be used to reveal the importance of the parameters tested. Thus, it succeeds in fulfilling its main objective: exploration of the system dynamics. As a further step, SINUSE can also be used to simulate management interventions, or changes in the rules or in the behavior of the actors.

CATCHSCAPE

Objective

Becu et al. (2003) have developed CATCHSCAPE, an agent-based model for the management of Mae Uam, a small catchment in Northern Thailand. CATCHSCAPE intends to explore the impact of upstream irrigation management on downstream agricultural viability in an environment where biophysical and social factors are a source of conflict. Thus, in an attempt to foster the achievement of negotiated settlements to such conflicts, it simulates the whole catchment features as well as farmer's individual decisions.

Modelling approach

CATCHSCAPE employs a sophisticated spatial representation of the catchment, which comprises two levels of organization: (i) the *land units*, combining soil texture, depth and land slope, and (ii) the *land use*, that can be paddy, upland or forest. Each paddy plot belongs to one of the six canals in the catchment, which are in turn organized in two irrigation schemes. Finally each irrigation scheme is part of a zone, corresponding to an actual village.

In this context, biophysical dynamics are simulated through a hydrological model and a distributed water balance taking into account each irrigation scheme's management, crop and vegetation dynamics.

As the focus of the model is on social interactions, the farmers are modelled as cognitive agents and a manager (cognitive) agent is assigned to each of the six canals in the catchment. Farmers employ a decision making mechanism to choose the most profitable crop according to their individual constraints. Moreover, they have to make decisions about land dynamics, choosing one of three opportunities: buying a plot, installing irrigation on upland (non-paddy) plots or converting forest plots to upland ones. An interesting feature is that the farmers' water expectation is continuously updated, thus introducing great interaction between socio-economic and biophysical dynamics. Finally, as far as irrigation management is concerned, the model involves three levels of control: the individual level, the canal and the irrigation scheme level.

Assessment

The objective of simulations conducted with the CATCHSCAPE model is not, of course, to provide accurate predictions of the future, as the model is only a sketch of the actual management procedure. Still, it provides a dynamic environment in which local stakeholders can explore the implications of alternative management approaches taking into account biophysical dynamics and social issues.

AWARE

Objective

Action-research and Watershed Analyses for Resource and Economic sustainability (AWARE) (Farolfi and Hassan, 2003) is a simulation tool that models the dynamics of catchment level water management in South Africa. The water management approach promoted by the National Water Act of South Africa relies on a licensing process, through which water use authorizations are allocated to various competing groups of users –communities, irrigation boards, forestry agencies and mines. In this context, AWARE is meant to be a support tool, evaluating the socio-economic and environmental consequences of alternative scenarios representing potential water management strategies.

Modelling approach

Two versions of the system were developed. The first one, AWARE1, adopts a simple approach, based on the assumption that supply remains fixed over time (at current levels). The Catchment Management Agency (CMA) reserves a certain water quantity for environmental purposes and allocates the remaining water employing one of various strategies prioritizing among different sectors of economic use. Each type of user pays a sector-dependent price per unit of water and finally makes an annual assessment. If water entitlements are less than satisfactory, reports of water shortage are sent to the CMA.

The demand for water by the users of each sector is modeled as a simple linear function. Changes in demand over time are based on the assumption that the different water use sectors grow (or decrease) at annual fixed rates.

AWARE2 is the second version of the system, which investigates the water allocation under equilibrium conditions. To this end, the model first calculates the equilibrium price and the resulting water subsidies (i.e. the difference between current water price and the equilibrium price) for each sector. Next, various strategies are simulated by changing sector subsidies, that is equivalent to using price as a market-based water allocation instrument.

As far as implementation is concerned, AWARE was originally conceived as a multi-agent system (MAS). However, the model's most recent version is a simulation model constructed in a programming language specifically designed for system dynamics modelling (SDM).

Assessment

AWARE focuses on the allocation of water entitlements among users or groups with conflicting economic interests. AWARE1 adopts a structure where supply remains fixed and demand steadily grows or decreases. Thus, it models a situation where water allocation can only be managed through command and control measures. On the other hand, AWARE2 investigates water allocation strategies under market clearing conditions, where market-based instruments, such as water tariffs, can be used to effectively allocate water. Both versions are not intended as prediction tools, but attempt to reveal the interconnections between strategic decisions and ecological and socio-economic elements of the system, thus providing a basis for discussion among stakeholders.

MANGA

Objective

MANGA (Bars et al., 2005) is a tool aiming to assist decision-makers in the difficult task of collective management of water resources. It provides a simulation environment for testing the consequences of various water allocation rules, in order to identify an acceptable compromise. Rule consequences depend on agricultural constraints, different actors' behaviours, and confrontation of their decision rules with other actors.

Modelling approach

MANGA is modelled as a MAS, with two types of agents: (i) *cognitive agents* (Farmers, Water supplier), who follow a cycle of perception-decision-action; and (ii) *reactive agents* (Information supplier, Crops, Climate), who follow a cycle of the perception-action type agent. There is no specified control agent and, thus, no central control point. Farmer agents compete over a limited water resource and negotiate in order to obtain the water they need.

The successive phases of a scenario simulation in MANGA are as follows:

(i) *Determination of the Cropping Plan*
Each farmer agent decides his cropping plan, based on individual parameters (cash, crop preferences, objectives, attitude toward risk) and agronomic rules (plot irrigation capacity, climate, crop yield).

(ii) *Negotiation Process between Farmers and Water Supplier Agents*
The water supplier agent receives a set of water requests and calculates the proposed amount of water for each farmer. These proposals depend on the water allocation rule being tested. Discussion and negotiation is possible between the farmer agents and the water supplier agent.

(iii) Climate Determination and Crop Growth

(iv) *Economic Results*
At the end of the year, each farmer agent calculates its yields and economic results. This information is synthesized by the information supplier agent and a global report is broadcasted to all farmers.

(v) *Decision-Making Processes*
Depending on their own and the global economic results, farmer agents decide whether to invest in more irrigation capacities and possibly change their behaviour by (a) imitating those that had the best results; or (b) calculating from its financial arrangements the investment cost and expected income.

The simulation results are analyzed from different viewpoints – individual, global, ethical and environmental – and presented to the users through appropriate interfaces.

Assessment

Although the model has not been applied to an actual study case, its validity has been tested in collaboration with decision-makers. Currently, MANGA is an operational tool that can be used to simulate different water allocation rules and investigate their consequences in terms of individual and collective production, disparities, and resource use. A future version of the system will elaborate on learning for the decision-making process and will integrate game theoretic principles in the negotiation mechanism.

The "Bali" model

Objective

The Lansing-Kremer model (Lansing and Kremer, 1993) simulates the irrigation system of the Oos-Petanu watershed in Bali. It involves the representation of the various water flows, the topology of rice terraces, as well as the coordination procedure used by local farmers for water allocation and pest control. The aim of the model is to prove that among the various levels of coordination for water sharing, the temple level, traditionally used, maximizes the production of rice. A further investigation tries to model the process of achieving this optimal scale of coordination as "adaptation on a rugged fitness landscape".

Modelling approach

The Bali irrigation system involves a complex network of terraces and weirs, along with various temples dedicated to water deities. Terraces, where rice is mainly cultivated, are organized in farmers' associations called subaks. On the other hand, the coordination of water sharing and cropping patterns is associated with a ritual calendar carried out at the temples. This ritual has been employed for hundreds of years and helps subaks ensure the viability of production, by balancing two opposing constraints: water sharing and control of pests.

The model developed by Lansing and Kremer defines the geographical setting in which subaks are located and also simulates the climatologic conditions, the crops' life cycle and the diffusion of pests. As far as farmers are concerned, the modelling is at the scale of subaks, each of which is attributed a cropping plan and a corresponding water demand.

Simulations with this model are used to compare, in terms of rice yield, the effects of different scales of coordination. More specifically, six levels are distinguished varying from one single cropping plan for the whole watershed to individual patterns for each of the subaks. The scale of coordination, that best approximates the temple level control, lies somewhere between these two extreme situations and was proved to achieve the highest rice yield.

In addition, the authors investigate the question of how the water temple scheme was historically developed. They propose that various coordination schemes may be seen as "a fitness landscape, in which the highest fitness peak is achieved by the temple scale of coordination" (Lansing and Kremer, 1993). A different set of simulations is run, where the coordination scheme is not predefined, but evolves gradually through an imitation procedure: subaks copy the cropping plan of their most successful neighbour. This procedure terminates when subaks have reached their local optimum and thus do not need to change their cropping plan anymore.

The result of the above simulations is the formation of different groups of subaks, sharing a common cropping plan. This is similar to a coordination scheme, as defined in the previous experiments. Various simulations were run, with a variety of cropping plans and environmental conditions, but still the same pattern evolved: after some iterations, the structure of coordinated subaks remarkably resembled the actual pattern of the water temples. Moreover, once this structure was formed, an additional property emerged: the network displayed increased levels of sustainability that enabled it to recover from extreme environmental conditions.

Assessment

Lansing and Kremer's model simulates the Balinese irrigation system under various environmental conditions and levels of coordination - from the farmer level up to the level of the watershed. Experiments confirm that the temple level, traditionally used by local farmers, is the level where decisions should be made in order for the rice yield to be maximized. However, Janssen (2006) suggests that a more comprehensive investigation of the agent deliberation mechanisms is needed for the model to overcome its sensitivity to assumptions of ecology and decision making.

The “Lake” model

Objective

Eutrophication is a widespread and growing problem of hydro-systems that is caused by an excess input of nutrients, like phosphorus. The model presented by Janssen (2001) specifically focuses on the management of lake eutrophication and explores the lake dynamics in relation to the behaviour of agents using phosphorus for agricultural purposes in the area.

Modelling approach

When intervening to limit eutrophication, reduced phosphorus levels may have unexpected results. Thus, successful management of lake eutrophication needs to take into account the behaviour of agents causing the non-point pollution. In this direction, the “Lake” model is an integrated model which combines a dynamic model of an ecosystem and a rule-based model of human behaviour.

The *lake ecosystem model*, defines the phosphorus life cycle and dynamics in the water and the mud of the lake, as well as in the soil around the lake. It calculates phosphorus levels, depending on these dynamics and on farmers’ behaviour. The latter may use phosphorus intensively or conservatively.

Human behaviour is described using a rule-based model of agents. Cognitive processing is employed to determine the use of phosphorus, depending on returns and uncertainty. Four different types of rules are distinguished, employed under different conditions of uncertainty and return levels:

(i) Deliberation is employed when both the levels of uncertainty and returns are low.
(ii) Social comparison involves copying the dominant behaviour of agents with comparable abilities when returns are low and uncertainty is high.
(iii) Repetition is employed when returns are high and uncertainty is low.
(iv) Imitation of the majority is employed when both returns and uncertainty are high.

During the simulation, the concentration of phosphorous in the lake is calculated, taking into account the phosphorus use of all agents and various random events. This calculated concentration, in turn, influences the individual returns of the agents.

Assessment

The “Lake” model is an integrated approach, studying the management of lake eutrophication. It combines non-linear ecosystem dynamics with a rule-based model of agents, using insights from social psychology. The model was not implemented for a specific case, making empirical validation impossible. However, conceptual validation has taken place with different experts and stakeholders to test the plausibility of assumptions.

COMMON ASPECTS AND CHARACTERISTICS OF AGENT-BASED MODELS FOR IRRIGATION MANAGEMENT

In the previous section, we reviewed a selection of representative test cases for the use of agent-based modelling in the field of irrigation management. In this section, we attempt to further explore the common aspects of the presented models and classify them according to their scale and extent of stakeholder participation.

Classification according to scale

The test cases presented in the previous section model the management of irrigated ecosystems in various scales.

Geographic Scale

The size of the target geographic area varies from a single irrigation scheme (SINUSE, SHADOC) up to a watershed covering thousands of hectares (“Bali” model). Fig. 1 illustrates the classification of the presented tools, along an increasing axis of target geographic area size.

Fig. 1. Agent-based models for irrigation management according to geographic scale

Representation Scale

The tools reviewed employ various scales of representation, in terms of the number of actors modeled and the number of agents used in simulation experiments. Table 1 summarizes these numbers for the tools that report such relative information.

Table 1. Agent-based models for irrigation management: actors modelled and number of agents used in simulation experiments

	Actors modeled	Number of agents used in simulations
SHADOC	Credit Manager (group agent) Pumping Station Manager (group agent) Watercourse Manager (group agent) Farmers	$30 \leq N_{farmer\ agents} \leq 100$ $7 \leq N_{group\ agents} \leq 11$
SINUSE	Farmers	120 farmer agents
CATCHSCAPE	Farmers Canal Managers	327 farmer agents 6 manager agents
AWARE	Catchment Management Agency (CMA) Large-scale commercial irrigation agriculture Smallholder irrigation farming Livestock producers Forestry farms Mining Industry Urban households Rural households	1 CMA 200 large-scale commercial irrigation farms 6000 smallholder irrigation farmers 20 livestock producers 30 forestry farms 20 Mines/quarries 30 industries 5 Urban Communities 20 Rural Communities
MANGA	Farmers Water supplier	100 farmer agents 1 water supplier agent 1 information supplier agent
“Bali” Model	Subaks (farmers’ associations)	172 subak agents
“Lake” model	Farmers	

Discussion

Contrasting the data on geographical scale and scale of agent representation, we observe that most irrigation management ABMS tools consider farmers at the scale of the individual (with the exception of the “Bali” model). Moreover, all DSSs of this type involve a single managing authority for water allocation, with SHADOC being the only model that defines a hierarchy of managers.

Moreover, it seems to be no direct analogy between the size of the geographic area targeted and the number of agents used in experiments. On the other hand, the scale of agent representation (individuals or groups) is a more decisive factor in defining the number of agents used in experiments: models aggregating water users into groups, usually instantiate one agent per group.

Classification according to stakeholder participation

Participatory methods and stakeholder participation are issues of paramount importance, as they allow for more effective and socially approvable models to be developed. Stakeholder involvement in the modelling phase can result in more plausible ABMS tools, as stakeholder behaviours, goals and perspectives are taken under consideration. Stakeholder participation in the validation procedure forms the basis for mutual understanding and enables the stakeholders to realize the assumptions and constraints of the models, thus improving stakeholders' trust in the models.

As far as the ABMS tools presented in this report are concerned, there is a wide range of participatory methods used in all phases of their development. Fig. 2 summarizes the participatory methods used in ABMS tools. Specifically, in the *modelling phase* some models involve extensive field surveys, while others employ theoretical modelling or interviews and dialog methods to elicit stakeholders' views. On the other hand, *validation* often involves non-participatory techniques, such as the comparison of the model outputs with statistical data or sensitivity analysis. However, stakeholder participation in this phase is also quite important and may be in the form of interviews and dialog sessions, RPG or actual deployment of the model in the studied area. Fig. 2 reveals that most of the reviewed ABMS tools involve some forms of stakeholder participation on one or more phases of their development.

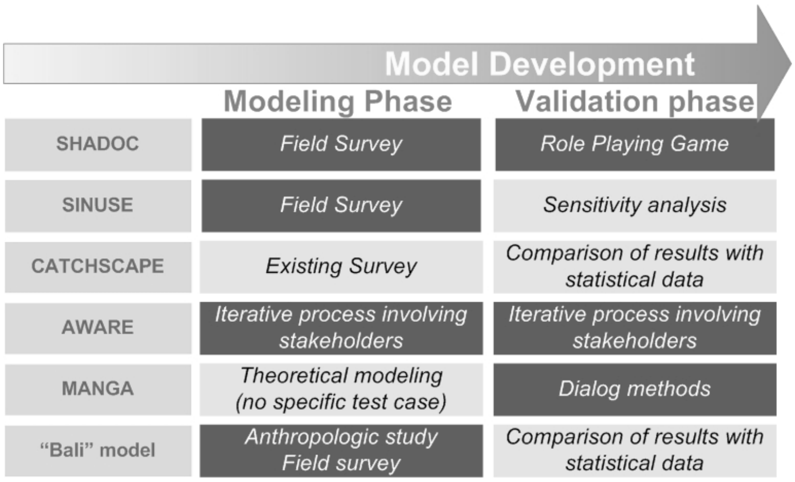

Fig. 2. *Stakeholder participation during the development phases of agent-based models for irrigation management*

ABMS TOOLS POTENTIAL AND CONSTRAINTS

Our study so far has demonstrated several cases where agent-based modelling has successfully been used to tackle with irrigation management problems, thus, showing a great potential for future DSS development. Even all reviewed approaches have quite diverge objectives, they still share the common goal of providing effective solutions and facilitating the decision-making processes for efficient water management. And the question that arises here is how and to what extent ABMS tools, as deployed in the reviewed models managed to achieve this common goal.

In order to support decision makers in the irrigation management sector, agent-based models are used to simulate physical, economic and social dynamics of certain systems, with the overall goal of estimating the effects of alternative management policies. This is not a trivial task, as it requires in-depth study of several factors and conditions, including water consumption demands and water assets availability. Even more, it requires critical ability and expertise for identifying the consequences of a certain policy in effect. Given these constraints, ABMS tools are not developed to forecast the exact state of the modelled system, but to explore how the system will evolve in view of a possible future (see also Athanasiadis et al., 2005).

This *non-predictive* nature of agent-based models poses a very important constraint to the process of evaluating a candidate management policy: the models' results have to be interpreted with care, according to their robustness and stability in a large number of runs and also across a wide range of parameter values. Even then, it is crucial not to overlook the constraints and assumptions of the model used, as simplifications are sure to exist and random variables are often employed at some point in the simulation flow.

That is where participatory methods come into play, as their effect on stakeholders' understanding of the model can prove invaluable. Various techniques can be employed, to engage stakeholders in a participatory process of communicating with the modellers, using the simulation tool and exploring its parameters, methods and constraints. In this way, they are engaged in a procedure that not only promotes their understanding of the model, but can also produce valuable feedback for socially validating the models, in terms of the different stakeholder perspectives.

The issue of validation of agent-based models is highly complicated and can be dealt with from various points of view. However, there are two dominant methods in the models presented in this paper. These are: (i) *conceptual validation*, that examines the plausibility of model assumptions; and (ii) *statistical validation*, that takes the traditional approach of comparing simulation results with real world data. The problem with both techniques is that they cannot be applied to social processes, as there are no analytic models for them and real world data from relevant surveys are rare and difficult to find. The solution may be found again in participatory techniques, as interviews and collaboration with stakeholders usually reveal a wealth of data on their social behaviour and the nature of the interactions between them.

Finally, we point out that the presented models, despite their diversity, have by no means exhausted the potential of ABMS in the irrigation management sector. A major challenge would be, for instance, the extension of the geographic scale of existing models, in order to target cross-boundary international management problems (as in cases where more than one countries share a water basin). This escalation, of course, requires more elaborate and fine-grained representations for the various aspects of water management and simulation models capable of incorporating multiple user behaviours combined with a variety of country-specific, or even local, management policies.

EPILOGUE – CONCLUSIONS

Developing DSS using agent-based modelling and simulation tools has been welcomed in the irrigation management sector, as it has a great potential in representing dynamic processes, and specifically social ones, in integrated assessment tools. On the other hand, though a promising and effective technique, ABMS has still not reached maturity and has to deal with various issues concerning: (i) the representation of social processes; (ii) dimensions of validation of the developed models; (iii) linking modelling and participation of stakeholders; and (iv) exploring wider application domains. However, ABMS tools bridge insights and concepts from several disciplines, including economics, psychology, sociology, environmental sciences, computer science and management sciences in an actor based analysis and modelling perspective for integrating social processes in water management DSSs.

For the researcher or decision maker interested in ABMS tools for irrigation management, we ended up to the following conclusions from our review:

(i) ABMS tools typically involve models with high uncertainty, thus they should be considered as tools for exploring future trends under specific scenarios, rather than accurate projections of the future (Athanasiadis et al. 2005).
(ii) ABMS tools can be validated either in a conceptual or a statistical fashion. However, social processes are very difficult to simulate as typically there are few data available on the level of the individual behaviour and decision making.
(iii) ABMS tools are complementary to participatory methods. They can be used as computer tools (games) for revealing to stakeholders the consequences of their actions or they can engage stakeholder in their development phase for assessing policy implications.

Finally, we draw the attention of future work for application areas of ABMS tools on cases that deal with shared water bodies among countries or regions where trans-border regulation and negotiation is required to be captured.

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