Water Resour Manage
DOI 10.1007/s11269-013-0394-0

A Framework for an Agent-Based Model to Manage Water Resources Conflicts

Masih Akhbari · Neil S. Grigg

Received: 13 August 2011 / Accepted: 16 June 2013

Abstract Competition for use of water is increasing and leads to many conflicts among competing interests with complex goals and water management systems. Technical system models are essential to create performance and other decision information, but models to simulate views of the competing parties are also needed to help resolve or mitigate conflicts. Agent-based models (ABMs) offer promise to fill this role, and in this study a new approach to agent-based modeling is introduced to simulate the behavior and interactions of the parties participating in a conflict scenario, which is modeled as a game. To develop this framework, we considered water issues of California's Sacramento-San Joaquin Delta region as an example of a long-standing situation, with emphasis on the San Joaquin watershed. However, this approach can be used in other watersheds and more complex systems. The ABM explains the interactions among the parties and how they can be encouraged to cooperate in the game to work toward a solution. The model also enables decision-makers to test management scenarios and understand the consequences of their decisions on different stakeholders and their behaviors.

Keywords Agent-based modeling · Conflict management · The Delta game · The San Joaquin watershed

1 Introduction

Uneven distribution of water in space and time along with population growth and negative impacts of human activities on the quality and quantity of water resources have created significant complexities in managing this vital resource. Water is almost never managed for a

---

M. Akhbari (✉)
Center for Watershed Sciences, University of California Davis, Davis, CA 95616, USA
e-mail: makhbari@ucdavis.edu

N. S. Grigg
Department of Civil and Environmental Engineering, Colorado State University, Fort Collins,
CO 80523-1372, USA
e-mail: neilg@engr.colostate.edu

single purpose, but is always managed with objectives of competing interests such as: agricultural, industrial and domestic uses, hydropower generation, recreation and environmental protection. This means that the management of water resources inherently involves conflicts among competing users who seek to exploit water for different purposes. Taking the objectives of all competing interests into account in decision making processes requires sophisticated approaches for managing water resources and requires analysis of both technical and human systems.

Among the many systems experiencing conflict, the Sacramento-San Joaquin Delta (the Delta) system has been dealing with complex conflicts for several decades. With some of the most fertile soils in the United States, agriculture is a multibillion-dollar industry (USDA 2009). The major cause of conflicts among stakeholders and competing interests in California has been the limited supply of water (Sheikh and Cody 2005). Enacting new regulations to prevent deterioration of the ecosystem and promote health of the region has created more limits to the water supply and new controversies among stakeholders over water supply distribution. Water diversions and new regulations to protect the Delta ecosystem create negative externalities on the parties, and the situation can be seen as a zero-sum game, where increasing the benefit to one party causes a reduction in the benefit to the other party.

Although many of the conflicts are purely political, there is broad agreement in the scientific community that one of the best paths to wise water management is a shared governance approach based on comprehensive analysis and facilitated stakeholder involvement. In this approach, all parties impacted by water resource decisions (such as system operators, public stakeholders, and agencies) are provided the opportunity to participate in model design, development, and evaluation. The goal is to provide these parties with a tool that increases understanding of the conflict and the ability to evaluate potential trade- offs (Lund and Palmer 1997).

Given the complexities of managing water resources, agent-based modeling (ABM) can be an effective approach to simulate the views of all parties required to help resolve the conflict (Bandini et al. 2009). Although it is relatively new, ABM has already become a widely used approach for the analysis, modeling and simulation of complex systems (Bandini et al. 2009). It is a basis for modeling social interactions among adaptive agents who influence each other according to the influences they receive (Macy and Willer 2002). An agent-based model provides a tool to represent the human decision-making process explicitly (Soman et al. 2008) and simulate agents' actual behaviors by delineating interactions among them (Edmonds et al. 2002; Terna 1998).

Galán et al. (2009) evaluated studies (Epstein 1999; Axtell 2000; Bonabeau 2002; Bousquet and Le Page 2004) of agent-based modeling and specified the advantages of this approach over the other modeling paradigms. Based on their study, using agent-based modeling, more natural and transparent descriptions of the systems can be provided; the hypothesis of homogeneity in the population can be relaxed; explicit representations of geographical environments can be incorporated; local interactions can be modeled; the bidirectional relationship between the individuals and the system can be modeled; the emergent behavior can be captured; the potential criticisms and suggested modifications to the model made by domain experts and stakeholders can be easily incorporated; and economic, social, territorial, technological, and every influential dimension can be included in a single model.

The first social agent-based simulation was developed by Thomas Schelling in 1978 to study housing segregation patterns. Agents in this simulation represented people and agent interactions represented a socially relevant process (Schelling 1978). Izquierdo et al. (2003)

developed an agent-based model, called FEARLUS-W, for river basin land use and water management to investigate ways of synthesizing stakeholder priorities. Their model was an extension of an already existing model, FEARLUS, developed by Polhill et al. (2001). Edwards et al. (2005) assessed the relevance of using an aggregate versus an agent-based (called individual-based in their study) model of water consumption according to the information available on the resource. Their model was the adaptation of Young's (1999) sociologic diffusion model for residential water domains.

Galán et al. (2009) developed an agent-based model for domestic water management in the metropolitan area of Valladolid, Spain. Zechman (2007) proposed a multi-agent modeling framework that combined agent-based, mechanistic, and dynamic methods to simulate contamination events. Using this simulation, she analyzed threat management strategies in water distribution systems. Kock (2008) used Agent-Based Modeling in Socio-Hydrological Systems. He developed two agent-based models of society and hydrology for Albacete, Spain, and the Snake River in eastern Idaho, USA, to investigate the societal effects of incorporating an additional institution to the existing water resources management institutions. Soman et al. (2008) developed a multi-agent based model to capture multiple farmer typology behaviors in making land use decisions that affect the production. Kennedy et al. (2010) developed an agent-based model to simulate conflicts between herdsmen in east Africa.

Chu et al. (2009) developed a Residential Water Use Model (RWUM) as a tool for urban water management to assess existing water usage policies and estimate potential water saving opportunities for future infrastructure development plans. Barthel et al. (2010) used the concepts of agent-based modeling to develop a multiactor-based model which simulates the decision-making process of the water supply sector. They used this model to specify critical regions for which adaptation strategies are required for water supply due to the effects of climatic change. Nikolic et al. (2013) integrated system dynamics simulation with agent-based modeling to provide support for integrated water resources management through analysis of spatial and temporal dynamics of water resources systems. Other examples for application of ABM in water resources include studies by Hare (2000) to control agricultural water pollution, Berger (2001) to manage agricultural land use and water resource, Tillman et al. (2001) to develop water supply system, and Bars et al. (2002) for water resource allocation and watershed management.

In this study, we show a new approach to simulate the process of encouraging parties who participate in a conflicting game to cooperate. This encouragement is accomplished through social and institutional enhancements in forms of providing incentives, penalties, and new regulations. For this purpose, a framework for an agent-based model, which simulates the behaviors of different water users/stakeholders of a system as well as their reactions to different management scenarios, is introduced. This model simplifies the complexity of considering all conflicting views and interactions of competing parties. The approach offers a powerful social network simulation tool that provides the opportunity to test new management scenarios and understand consequences of decisions in a simple, but still reliable, form without requiring the user to develop complex formulas for a new scenario. It also helps to determine the effectiveness of implementing different social and institutional enhancements for reducing conflict levels. The model should be combined with a continuous watershed simulation model to consider the influence of actions taken by the agents on quality and quantity of flows as well as water demands with a dynamic approach. This way, the model can be used to set up rules corresponding to time-varying water demands and environmental concerns. It is parameterized for the San Joaquin watershed in California, but can simply be adjusted to be used for other watersheds.

2 Agent Based Modeling

In agent-based modeling, agents are defined as autonomous entities that have particular knowledge and information (Parker et al. 2003). They can interact with other agents and with a common environment. Agents are goal directed; can act upon the environment; and can react to policy and market conditions (Wooldridge and Jennings 1995). They are characterized by their attributes, behavioral rules, memory, decision-making sophistication (the amount of information an agent requires to make decisions), and resources/flows. An agent can be any type of independent component such as software, model, individual, organization, group, etc. (Bonabeau 2002). In applications of ABM to social processes, people or groups of people are considered to be agents, and agent relationships represent processes of social interaction (Gilbert and Troitzsch 1999). It should be noted that in this approach, it is assumed that people and their social interactions can be plausibly modeled at some reasonable level of abstraction for well-defined purposes (Macal and North 2006a).

The environment, interacting with the agents, includes pertinent elements of the simulated system that are not agents. It determines the overall dynamics of the system and effects that influence agents. In general, the environment provides agents with their perceptions, which are relative to the current structure of the system and to the arrangement of agents living in it (Bandini et al. 2009).

In ABM approach, the system is formulated from the perspectives of the individual agents, which are modeled as discrete autonomous entities with particular goals and actions (Ng et al. 2010). In comparison with traditional models, ABMs are flexible, they capture emergent phenomenon, and incorporate real world systems involving complex human decision-making (Bonabeau 2002). The key steps in developing an agent-based model are (Macal and North 2006a, b):

1. Identifying agents;
2. Accurately specifying their distinct behaviors;
3. Defining the environment the agents live in and interact with;
4. Identifying the agents relationships and develop a theory about their interactions with each other and the environment;
5. Developing essential agent-related data;
6. Appropriately representing agent-to-agent interactions as well as agent-environment interactions;
7. Validating the agent behavior model.

2.1 Classification of Agents' Behaviors and Interactions

Bandini et al. (2009) classified agents' behaviors into reactive and deliberative. Reactive agents have a defined position in the environment. Their actions are the consequences of their perception of stimuli (events in the environment that influence behavior). This perception comes either from other agents or from the environment. Therefore, reactive agents' behaviors are specified as a set of condition-action rules coupled with a selection strategy which helps to choose an action to be taken whenever different rules are activated. For deliberative, also called cognitive agents, the selection mechanism is more complex. Their behavior is based on agent knowledge about the environment and on memories of past experiences.

In addition to reactive and deliberative agents, a third class can also be defined called Hybrid, which is a combination of reactive and deliberative agents. In this class, agents can have a layered architecture. The structure of layers can be vertical or horizontal (Brooks

1986). There are no priorities associated to horizontal layers. In this structure, to analyze the agent's behavior, the results of the different layers must be combined. In vertical structure, there is a higher priority for reactive layers compared to deliberative ones and these layers are activated only when no reactive behavior is triggered.

The agent interaction models can be categorized into two models: *direct* and *indirect* interactions. In the former, which is the most widely adopted model, there is a direct information exchange between involved agents. In the indirect interaction models, an intermediate entity mediates agent interactions. This entity can even regulate the interactions (Bandini et al. 2009).

3 The Delta Game

California is the largest agricultural producer in the United States, and the national leader in agricultural exports. In addition, agriculture supports more than 150,000 jobs in the state. However, agricultural return flows increase salinity rates in the rivers, threatening aquatic life and environmental health. Increasing salinity, as the key water quality issue in California (Peterson et al. 1996), with the current rate threatens to impose substantial costs to this state, impact income, and causes significant job losses (Howitt et al. 2009).

For decades, there have been serious conflicts over how water resources are managed in California. Debates over whether or not to transfer water from the Delta region to users elsewhere, and how to transport the water, have been the root causes of the conflicts in California (Hanemann and Dyckman 2009). The conflicting situations became more complex after more limitations were imposed to the supplying system due to new regulations enacted to protect the region's ecosystem.

To deal with the conflicting issues in the region, a variety of innovative ideas have been developed. However, the main criticism is that they do not have an overall framework. The most comprehensive effort to resolve water resources conflicts in the region has been the California Bay-Delta Program (CALFED) which was initiated in 1995. CALFED designated the "problem area" as the Delta, and the "solution area" as all areas hydraulically connected to the Delta or relying on its water supplies, mainly Sacramento and San Joaquin Rivers (CALFED 2000). Addressing three main problems was the focus of the program: ecosystem health, water quality, and water supply reliability. Early in the program, the CALFED agencies decided the program needed to engage the public, particularly from identified interest groups or NGOs. One of the best and earliest achievements of CALFED was public awareness and their participation in water conservation activities (Macaulay 2001).

Nevertheless, besides the strong scientific fundamental and comprehensive and adaptive planning for the CALFED program, it seems that it has not been successful after years of implementation. Hanemann and Dyckman (2009) claimed that the CALFED has not been able to eliminate the zero-sum aspect of the game through collaborations, negotiations and collective decision-making by stakeholders. A review by the Little Hoover Commission (2009) found CALFED to be "costly, underperforming, unfocused and unaccountable". The significant disagreement about the property rights and the fact that actors prefer to spend their energy fighting to change their property rights rather than accommodating to them has created an intangible situation for the bargaining solution.

Therefore, to deal with the conflict and resolve it, some major changes in policy are required to help protect the Delta against collapse (Lund et al. 2007, 2010). Madani and Lund (2012) evaluated the nature of the conflicts in the Delta Region. The main conclusions of their study are summarized in the following. For half a century, the nature of the conflicts in the Delta has had a Prisoners' Dilemma game-theoretical structure, when all sides of the conflict prefer to act individually and not to cooperate. This behavioral strategy ultimately causes the Pareto optimum solution to be less than when all parties cooperate. Nowadays, due to the deterioration of the Delta and more environmental, social, and political limitations, some parties have to compromise and cooperate. This situation is called a chicken game, when a party (especially the one with higher risk aversion) agrees to cooperate and become the chicken. In chicken games, the dominant strategy of the parties is to wait as long as possible to force the other parties to deviate from non-cooperative strategies. However, since a collapse can impose significant costs to the state and stakeholders, the sooner the parties cooperate, the lower losses for the state and parties involved.

4 Proposed Agent-Based Model

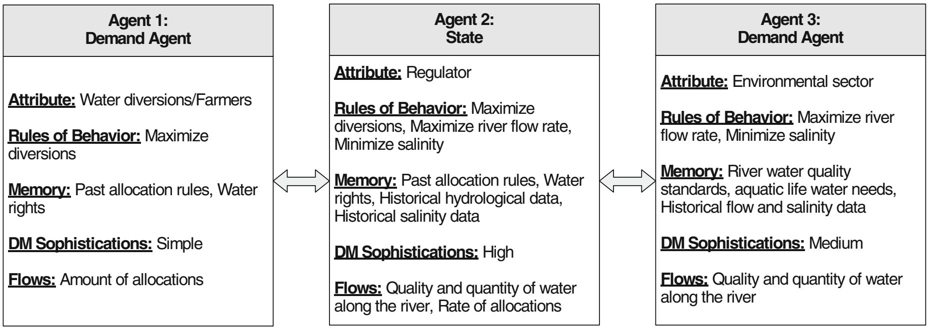
The ABM proposed in this study is intended to provide a tool that helps to find effective management scenarios to encourage conflicting parties to cooperate. It uses a new approach to consider parties' reactions to new decisions and to formulate suggested social and institutional enhancements. In formulating the system, the complexity of taking views and interactions of competing parties into account is simplified. Combining this ABM with a continuous watershed simulation model makes it capable of evaluating the influence of implementing new management scenarios on quality and quantity of flows as well as other water demands. This watershed simulation model also helps to consider the dynamics of the system and timing of flow and allocations.

To develop an ABM for the situation in the Delta, the environment must be considered as the entire Delta system. This includes all areas hydraulically connected to the Delta. The agents must be assigned as all water users, operators, stakeholders, and parties of interest. However, due to computational restrictions, the system is simplified and this study is accomplished on only a portion of the area. The environment is considered to be the San Joaquin watershed. The San Joaquin River is one of the two main rivers discharging into to Delta, in addition to the Sacramento River. Due to the significant agricultural activities and high salinity concentrations in the river, conflicts have been raising over its water quality management. To manage these conflicts, a simulation of the San Joaquin watershed is considered as the environment for the proposed ABM.

In this study's simplified approach, agents are defined as a decision-making agent, the state; and demand agents: water diversions/farmers (demanding for water), and the environmental sector (demanding for enough water flowing along the river with an acceptable quality). The "diversions/farmers" will be referred to as "diversions" hereafter. The State agent can be represented as a deliberative agent having direct interactions with the others, while the other two are reactive agents having indirect interactions with each other. Figure 1 shows the characteristics of each agent.

It should, however, be noted that in the actual scenario, the system is significantly more complex. Federal agencies as well as all other governing units can be considered decision-makers in addition to the state. Furthermore, different types of diversion agents can be defined based on the fact that some diversions might be concerned about the environment and cooperate; some might obtain more benefits by cooperation and have more willingness to cooperate; and some might not care about the environment and be persistent in noncooperation.

The action/behavior of each agent is based on its perception about the system and the problem. Their perception can be influenced by the environment as well as pressure from other agents. Figure 2 shows the overall influence of the environment and the agents on each



Agent 1: Demand Agent

Attribute: Water diversions/Farmers

Rules of Behavior: Maximize diversions

Memory: Past allocation rules, Water rights

DM Sophistications: Simple

Flows: Amount of allocations

Agent 2: State

Attribute: Regulator

Rules of Behavior: Maximize diversions, Maximize river flow rate, Minimize salinity

Memory: Past allocation rules, Water rights, Historical hydrological data, Historical salinity data

DM Sophistications: High

Flows: Quality and quantity of water along the river, Rate of allocations

Agent 3: Demand Agent

Attribute: Environmental sector

Rules of Behavior: Maximize river flow rate, Minimize salinity

Memory: River water quality standards, aquatic life water needs, Historical flow and salinity data

DM Sophistications: Medium

Flows: Quality and quantity of water along the river

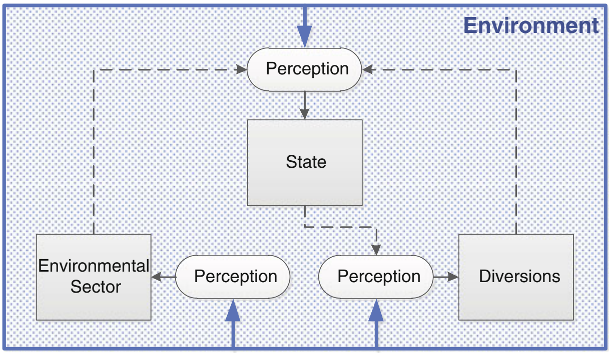
Fig. 1 Agents in the study area and their characteristics

other. As shown in this figure, the environment influences the perceptions of all agents, because the environment determines water availabilities and limitations of the system. Both diversions and environmental sector influence the perception of the state by informing it about the concerns and demands, and justifying the importance of their goals. In addition, the State affects the perception of the diversions by informing them about the new regulations, educational plans, assigned incentives, etc. The environmental sector's perception is only influenced by the environment.

Figure 3 illustrates details of the agent-to-agent and agent-environment interactions. The State agent has a direct interaction with both diversions and environmental sector, but there is an indirect interaction between the diversions and the environmental sectors, having the state as the intermediate/mediator agent. As demonstrated in Fig. 3, the environment determines the quality and quantity of water along the river as well as water available for allocations; while the interaction of all agents determines agricultural water demands for the environment. In indicating their water demands, diversions may have two types of behaviors: cooperative, and non-cooperative. In the case of cooperation, supplying their total demand will be compatible with the system's capability of supplying water and will not harm the environment. Therefore, the negative externalities between the diversions and environmental sector might be reduced to an unimportant level and the environmental sector might compromise minor violations.

Diversions' non-cooperative behavior may result in three possible reactions from the environmental sector. If the impact of not cooperating in regard to the quantity and quality of

Fig. 2 The influence of the environment and other agents on each agent



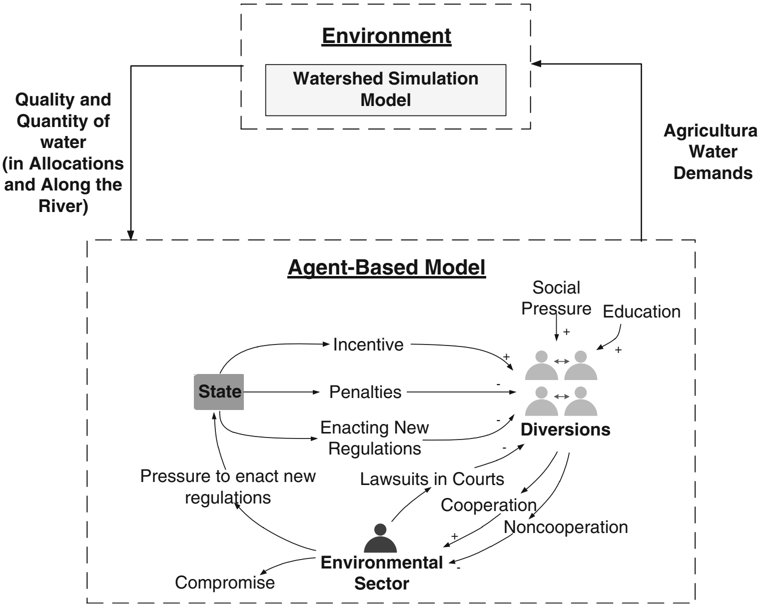


Fig. 3 Agent-to-agent and agent-environment interactions

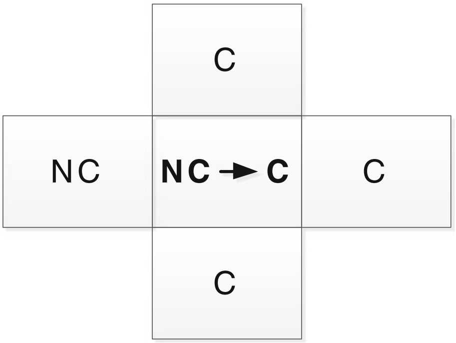
the river water is minor or negligible, the environmental sector may compromise; otherwise, it may file a lawsuit, or put pressure on the state to create more limitations through enacting new regulations in order to protect the river's aquatic and environmental health. Meanwhile, the state can provide some incentives (as financial aids or loans) to encourage cooperative behavior. It can also consider some penalties for violators. Enacting new regulations can also result in more pressure on diversions to cooperate.

In addition to pressures from the environmental sector and the state's policies, social pressure and education are two other factors influencing the diversions' willingness to cooperate. Edwards et al. (2005) implies that in addition to an agent's personal interest, social pressure (influence of the behavior of its neighbors) has considerable effect on the decision of the agent to change its behavior. Figure 4 shows the impact of social pressure. Cooperation and noncooperation are, respectively, represented by "C" and "NC" in this figure. According to this figure, when the majority of the neighbors of an agent are of a certain type (cooperative in this figure), the agent is more likely to change its initial behavior to match its neighbors. In addition to the social pressure, increasing the knowledge of the parties in order to change their perception about the region's future can help encourage them to shift from their self-optimizing attitude. Education and social learning could change the stakeholders' perceptions that the status quo ultimately could end up with failure and will result in less benefit since the stakeholders should solve the problem on their own.

5 The ABM Formulation

As mentioned earlier, the environment determines available water for allocations to diversions. These allocations may or may not satisfy diversions or environmental agents. In the case of dissatisfaction, these agents interact and influence each other's behavior. Then,

Fig. 4 The influence of the social network on each agent



the diversions specify their new water demands based on the interactions they had with each other and with other types of agents. This procedure is formulated as follows:

Total available water to be allocated to diversions is calculated by deducting the environmental minimum flow requirement from the total inflows (from precipitation, upstream inflow and tributary inflows) as shown in Eq. 1. This value is then divided by the total area of agricultural lands in the study area and then multiplied by the area of each individual land *i* to determine the total water available for that diversion (Eq. 2). If the water demand requested by agent *i* is more than the available water for this agent, the behavior of this agent is considered non-cooperative; otherwise, the agent is cooperating (Eq. 3).

$$TAW = \sum_{in=1}^{N} Q_{in} - Q_{\min}; \qquad \forall y, m \tag{1}$$

$$AW_i = \left[TAW \Big/ \sum_{i=1}^{I} LA_i \right] \times LA_i; \quad \forall y, m \tag{2}$$

$$\begin{cases} if\ AW_i < D_{\max,i} => i \rightarrow NC \\ if\ AW_i \geq D_{\max,i} => i \rightarrow C \end{cases} \tag{3}$$

where,

TAW	is the total available water (cms)
Q_{in}	is the inflow to the river from the upstream and all tributaries (cms)
Q_{min}	is the minimum river water flow rate required for environmental purposes (cms)
AW_i	is the amount of available water for diversion *i* (cms)
LA_i	is the area of the land belong to diversion *i* (hectare)
$D_{max,i}$	is the maximum water demand for water user *i* (cms)
m	is the number of months (from 1 to 12); and,
y	is the number of years in the time series.

After designating the cooperative and non-cooperative agents, it is determined at what degree an agent is willing to change its behavior. The utilities of different agents, U_i, to change or keep their current behaviors are determined using Eqs. 4 through 7. These formulas are based on Edwards et al.'s (2005) adaptation of Young's (1999) sociologic diffusion model for residential water domains.

$$U_i(C \rightarrow C) = a \times V_i(C) + F_m \tag{4}$$

$$U_i(C \rightarrow NC) = b \times V_i(NC) \tag{5}$$

$$U_i(NC \rightarrow C) = c \times V_i(C) + F_m \tag{6}$$

$$U_i(NC \rightarrow NC) = d \times V_i(NC) \tag{7}$$

where, $U_i(C \rightarrow C)$ is the utility of agent i having behavior C and is willing to keep its behavior, $U_i(C \rightarrow NC)$, is the utility of agent i having behavior C and deciding to change its behavior, $V_i(C)$ and $V_i\ (NC)$ are the proportions of neighbors of agent i of behavior C and NC, respectively. a, b, c, and d are parameters of the model. Edwards et al. (2005) considered $a{=}b{=}0.7$ and $b{=}c{=}0.3$. F_m is the modification factor and is a function of water availability, education, and pressures from the environmental sector and the State. In the above equations, the first term on the right-hand side represents the social pressure and the second term (in Eqs. 4 and 6) represents the pressures from the other agents and the environment as well as the effect of education.

If there is enough water available to allocate to the water users, $F_m = F_m{}^*$ and:

$$F_m^* = \begin{cases} 1-[a \times V_i(C)] & For \quad Eq.4 \\ 1-[c \times V_i(C)] & For \quad Eq.6 \end{cases} \tag{8}$$

Substituting F_m^* in Eqs. 4 and 6 results in $U_i = 1$ (or 100 % utility). In other words, since the available water can supply the agent i's demand, this agent is considered as a cooperative agent. Table 1 presents different values of modification factor due to various actions taken by the other agents. According to this Table, if the environmental sector files a lawsuit in a court, or if the State enacts new regulations, the diversions are obligated to cooperate. In this case, the modification is considered equal to F_m^* in order to achieve 100 % utility for the corresponding agent to cooperate. In case the environmental sector compromises, there will not be any pressure on the agent to cooperate. The agent might only be influenced by its social network (the neighbors) in this case. Therefore, the value of modification factor is considered equal to zero. Supposing that the state provides some incentives to encourage diversions to cooperate, the value of the modification factor is corresponding to the amount of incentives provided. In other words, a diversion's benefit might be reduced due to cooperation. The percentage of this reduced benefit that is compensated by the incentives is considered as the modification factor. Clearly, to encourage diversions to cooperate, the state does not need to compensate 100 % of the lost benefit due to the fact that social pressure makes up a portion of it. The State can also consider some penalties for the violators. In this case, the modification factor will be a function of the negative impacts of (or damages resulted from) the agent's noncooperation (its extra water demand and/or the

Table 1 Modification factors for different state and environmental sector pressure

Category	Action	Modification factor
Legal	Filling a lawsuit in a court	$F_m = F_m^*$
	Environmental sector compromises	$F_m = 0$
Management	Providing incentives by the State	$F_m =$ Percent of the lost benefit
	Considering penalties by the State	$F_m = f(D_{\max,i})$
	Education	$F_m = f(PV|future\ damages)$
Legislative	Enacting new regulations	$F_m = F_m^*$

salinity of its return flow). The modification factor for education is determined based on the diversions' change of perception about the future. Therefore, it will be set as a function of the present value of potential future damages to the system.

Now, the demand modification rate for agent i, D_i^m, is calculated as following:

$$\begin{cases} D_i^m = \left(D_{\max,i} - AW_i\right) \times (1 - U_i); & \forall y, m, D_{\max,i} > AW_i \\ D_i^m = 0; & \forall y, m, D_{\max,i} \leq AW_i \end{cases} \tag{9}$$

and the agent i's new maximum demand, ND_i, is determined as:

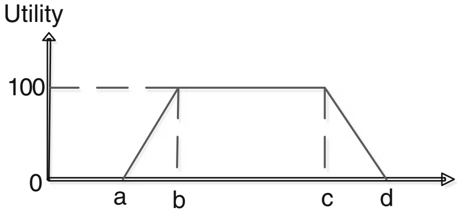
$$ND_{\max,i} = AW_i + D_i^m; \quad \forall y, m \tag{10}$$

In case of a water shortage, if the agent cooperates, $U_i = 1$, the agent's demand modification rate will be zero; and therefore, its new demand will be equal to the available water. Otherwise, its demand modification rate will be greater than zero, and the agent claims for more water than what is available. However, this new demand might not be the same as the agent's initial water demand, since it has been influenced by the society, environment, and other agents.

6 Measures

To evaluate the performance of the proposed ABM and effectiveness of the defined scenarios a measure is required. This measure may determine the level of water user's/stakeholder's satisfaction due to the allocations and decisions made. For this purpose, the utility functions of different water users/stakeholders can be considered as a satisfaction measure. The general form of a utility function is shown in Fig. 5. The vertical axis represents the utility in the scale of 0 to 100 % and the horizontal axis depends on the type of stakeholder the utility function is being developed for. For diversions, the horizontal axis

Fig. 5 The general form of a utility function



shows the range of allocations. For the environmental sector, two utility functions should be developed: one representing flow rate along the river and the other one expressing water quality (e.g. salinity concentration for the San Joaquin River).

Using these utility functions, each water user's/stakeholder's utility relative to its allocated water or the quality of water along the river can be determined due to all scenarios. These utilities can then be compared with the corresponding ones in the status quo. The final step would be to check if the existing conflicts have been reduced. If there is any increase in the utilities of water users/stakeholders, it can be claimed that the conflicts have been reduced.

7 Conclusion

To deal with the complex conflicting situations such as the one in the Delta area, some major changes in policy are required. In these types of conflicting situations, the dominant strategy of the conflicting parties is to wait as long as possible to force others to cooperative, so that they can benefit from their noncooperation strategies. However, since a collapse of the system can impose significant costs to both the governing units and water users/stakeholders, the sooner the parties cooperate, the less damage may occur. To find out effective strategies and water resources management policies that encourage parties to cooperate, an operational model capable of simulating the stakeholders' interactions is required as a tool.

However, to simulate the more complex societal systems nowadays, more powerful and sophisticated modeling tools are needed. Agent-based modeling is one of the newly developed efficient tools that can be used to simulate complex systems with interactive components. This study proposed an ABM framework which helps to find effective management scenarios for encouraging conflicting parties to cooperate. Some social and institutional enhancements were formulated, in forms of providing incentives, penalties, new regulations, etc., and introduced to the ABM model as encouragement strategies. This model can be used to manage conflicts in complex water resources systems. It provides a clear description of humans/organizations interactions and a better understanding of complex interactive systems by simplifying the complexity of considering views and interactions of competing parties. Using this proposed ABM, decision-makers will have more reliable support for their decision-making processes.

Although this model has specifically been parameterized for the San Joaquin watershed, California, it can simply be adjusted to be used for other watersheds and more complex systems. More management scenarios can also be defined and easily introduced to this model to designate the most effective scenarios for encouraging different parties to cooperate in the game. Therefore, new management scenarios can be evaluated without requiring the user to develop and deal with complex formulas. Combining this ABM with a continuous watershed simulation model helps to designate effective social and institutional enhancements in improving the quality and availability of flows, which results in reduced conflict levels. This model is a powerful tool that helps to set up rules based on the timing of flows, water demands, and environmental concerns.

References

Axtell RL (2000) Why agents? On the varied motivations for agent computing in the social sciences. In: Macal CM, Sallach D (eds) Proceedings of the workshop on agent simulation: applications, models, and tools. Argonne Natl. Lab, Argonne, pp 3–24

Bandini S, Manzoni S, Vizzari G (2009) Agent-based modeling and simulation: an informatics perspective. J Artif Soc Social Simul 12(4):4, http://jasss.soc.surrey.ac.uk/12/4/4.html

Bars ML, Attonaty JM, Pinson S (2002) An agent-based simulation for water sharing between different users. In: International proceedings of the first international joint conference on autonomous agents and multi agent systems, Bologna, Italy

Barthel R, Janisch S, Nickel D, Trifkovic A, Hörhan T (2010) Using the multiactor-approach in GLOWA-Danube to simulate decisions for thewater supply sector under conditions of global climate change. Water Resour Manag 24:239–275. doi:10.1007/s11269-009-9445-y

Berger T (2001) Agent-based spatial models applied to agriculture: a simulation tool for technology diffusion, resource use changes and policy analysis. Agric Econ 25(2–3):245–260. doi:10.1111/j.1574-0862.2001.tb00205.x

Bonabeau E (2002) Agent-based modeling: methods and techniques for simulating human systems. Proc Natl Acad Sci 99(suppl 3):7280–7287

Bousquet F, Le Page C (2004) Multi-agent simulations and ecosystem management: a review. Ecol Modell 176:313–332. doi:10.1016/j.ecolmodel.2004.01.011

Brooks RA (1986) A robust layered control system for a mobile robot. IEEE J Robot Autom 2:14–23

CALFED (2000) Implementation plan. Final Programmatic EIS/EIR Technical Appendix

Chu J, Wang C, Chen J, Wang H (2009) Agent-based residentialwater use behavior simulation and policy implications: a case-study in Beijing City. Water Resour Manag 23:3267–3295. doi:10.1007/s11269-009-9433-2

Edmonds B, Bartheleny O, Moss S (2002) Domestic water demand and social influence: an agent-based modeling approach. CPM Report 02–103

Edwards M, Ferrand N, Goreaud F, Huet S (2005) The relevance of aggregating a water consumption model cannot be disconnected from the choice of information available on the resource. Simul Model Pract Theory 13(4):287–307, Available at: 10.1016/j.simpat.2004.11.008 [Accessed April 28, 2011]

Epstein JM (1999) Agent-based computational models and generative social science. Complexity 4:41–60. doi:10.1002/(SICI)1099-0526(199905/06)4:5<41::AID-CPLX9>3.0.CO;2-F

Galán JM, López-Paredes A, del Olmo R (2009) An agent-based model for domestic water management in Valladolid metropolitan area. Water Resour Res 45, W05401. doi:10.1029/2007WR006536

Gilbert N, Troitzsch KG (1999) Simulation for the social scientist. Open University Press, Buckingham

Hanemann M, Dyckman C (2009) The San Francisco Bay-Delta: a failure of decision-making capacity. Environ Sci Policy 12(6):710–725

Hare MP (2000) Agent-base integrated assessment of policies for reducing groundwater pollution by nitrates from agricultural fertilizer, part I: pilot study model description and initial results. Working Report, Swiss Federal Institute of Environmental Science and Technology

Howitt RE, Kaplan J, Larson D, MacEwan D, Medellín-Azuara J, Horner G, Lee NS (2009) The economic impacts of Central Valley salinity. University of California Davis, Final Report to the State Water Resources Control Board Contract 05-417-150-0

Izquierdo LR, Gotts NM, Polhill JG (2003) FEARLUS - W: an agent-based model of river basin land use and water management. In: Dijst M, Schot P, de Jong K (eds) Framing land use dynamics. Reviewed abstracts International Conference, Faculty of Geographical Sciences, Utrecht University, Utrecht, The Netherlands, 16–18 April 2003. pp 163–165

Kennedy WG, Hailegiorgis AB, Rouleau M, Bassett JK, Coletti M, Balan GC, Gulden T (2010) An agent-based model of conflict in East Africa and the effect of watering holes, Proceedings of the 19th Conference on Behavior Representation in Modeling and Simulation, Charleston, SC, 21–24 March 2010

Kock BE (2008) Agent-based models of socio-hydrological systems for exploring the institutional dynamics of water resources conflict. MS Thesis, Massachusetts Institute of Technology

Little Hoover Commission (2009) Clearer structure, cleaner water: improving the performance and outcomes at the state water boards. State of California, Sacramento, CA

Lund JR, Palmer RN (1997) Water resource system modeling for conflict resolution. Water Resources Update, Issue No. 108, Summer, pp. 70–82

Lund JR, Hanak E, Fleenor W, Howitt R, Mount J, Moyle P (2007) Envisioning futures for the Sacramento-San Joaquin Delta. Public Policy Institute of California, San Francisco, CA, 300 pp. http://www.ppic.org/content/pubs/report/R_207JLR.pdf

Lund JR, Hanak E, Fleenor W, Bennett W, Howitt R, Mount J, Moyle P (2010) Comparing futures for the Sacramento-San Joaquin Delta. University of California Press, Berkeley

Macal CM, North MJ (2006a) Tutorial on agent-based modeling and simulation part 2: how to model with agents. Proc. of 2006 Winter Simulation Conference, pp.73–83

Macal CM, North MJ (2006b) Introduction to modeling and simulation (37 presentation slides). MCS LANS Informal Seminar, Argonne National Library, Available at: www.cas.anl.gov, Accessed March 29 2010

Macaulay S (2001) Resolution of water resources issues in the State of California. United States of America: The CALFED Bay-Delta Program, presented at III Encuentro de las Aguas, October 24–26, 2001, Santiago, Chile

Macy MW, Willer R (2002) From factors to actors: computational sociology and agent-based modeling. Annu Rev Sociol 28:143–166

Madani K, Lund JR (2012) California's Sacramento-San Joaquin Delta conflict: from cooperation to chicken. Water Resour Plan Manag 138(2):90–99

Ng T, Eheart J, Cai X, Braden JB (2010) A watershed-scale agent-based model incorporating agent learning and interaction of farmers' decisions subject to carbon and Miscanthus prices. American Geophysical Union, Fall Meeting 2010, abstract #H43C-1252

Nikolic VV, Simonovic SP, Milicevic DB (2013) Analytical support for integrated water resources management: a new method for addressing spatial and temporal variability. Water Resour Manag 27:401–417. doi:10.1007/s11269-012-0193-z

Parker DC, Manson SM, Janssen MA, Hoffmann MJ, Deadman P (2003) Multi-agent systems for the simulation of land-use and land-cover change: a review. Ann Assoc Am Geogr 93(2):314–337

Peterson DH, Cayan DR, Dettinger MD, Noble M, Riddle LG, Schemel LE, Smith RE, Uncles RJ, Walters R (1996) San Francisco Bay salinity: Observations. Numerical simulation, and statistical models. In: Hollibaugh JT (ed) San Francisco Bay–the ecosystem: San Francisco. American Association for the Advancement of Science, Pacific Division, pp 9–34

Polhill JG, Gotts NM, Law ANR (2001) Imitative versus non-imitative strategies in a land use simulation. Cybern Syst 32:285–307

Schelling TC (1978) Micromotives and macrobehavior. Norton, New York

Sheikh PA, Cody BA (2005) CALFED Bay-Delta Program: overview of institutional and water use issues. Congressional Research Service, Library of Congress, Washington, D.C., p 16

Soman S, Misgna G, Kraft S, Lant C, Beaulieu J (2008) An agent-based model of multifunctional agricultural landscape using genetic algorithms. 2008 Annual Meeting, July 27–29, 2008, Orlando, Florida 6142, American Agricultural Economics Association (New Name 2008: Agricultural and Applied Economics Association)

Terna P (1998) Simulation tools for social scientists: building agent based models with SWARM. JASSS 1(2). http://www.soc.surrey.ac.uk/JASSS/1/2/4.html

Tillman D, Larsen TA, Pahl WC, Gujer W (2001) Interaction analysis of stakeholders in water supply systems. Water Sci Technol 43(5):319–326

United States Department of Agriculture (2009) Trade and agriculture: what's at stake for California? Foreign Agriculture Service, Available at http://www.fas.usda.gov/info/factsheets/wto/states/ca.html

Wooldridge MJ, Jennings NR (1995) Intelligent agents: theory and practice. Knowl Eng Rev 10(2):115–152

Young HP (1999) Diffusion in social networks. Work. Pap. 2, Brookings Inst., Washington DC

Zechman E (2007) Agent-based modeling to simulate contamination events and to analyze threat management strategies in water distribution systems. In: Proceeding of the world environmental and water resources congress, Tampa, FL, May 2007