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ORIGINAL ARTICLE

Capturing the complexity of water uses and water users within a multi-agent framework

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Abstract Due to the hydrological and socio-economic complexity of water use within river basins and even sub-basins, it is a considerable challenge to manage water resources in an efficient, equitable and sustainable way. This paper shows that multi-agent simulation (MAS) is a promising approach to better understand the complexity of water uses and water users within sub-basins. This approach is especially suitable to take the collective action into account when simulating the outcome of technical innovation and policy change. A case study from Chile is used as an example to demonstrate the potential of the MAS framework. Chile has played a pioneering role in water policy reform by privatizing water rights and promoting trade in such rights, devolving irrigation management authority to user groups, and privatizing the provision of irrigation infrastructure. The paper describes the different components of a MAS model developed for four micro-watersheds in the Maule river basin. Preliminary results of simulation experiments are presented, which show the impacts of technical change and of informal rental markets on household income and water use efficiency. The paper also discusses how the collective action problems in water markets and in small-scale and large-scale infrastructure provision can be captured by the MAS model. To promote the use of the MAS approach for planning purposes, a collaborative research and learning framework has been established, with a recently created multi-stakeholder platform at the regional level (Comisión Regional de Recursos Hidricos) as the major partner. Finally, the paper discusses the potentials of using MAS models for water resources management, such as increasing

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transparency as an aspect of good governance. The challenges, for example the need to build trust in the model, are discussed as well.

Keywords Multi-agent systems · Simulation models · Integrated water resources management · Collective action · Trade of water rights · Innovations · Chile

1. Introduction

The management of water resources in an integrated and sustainable way is usually complex. This is due to the fact that the scale of management implied by hydrological characteristics often comprises many layers of social, political, and economic institutions. Even at the sub-basin level there may be manifold users such as local small-scale farmers, large-scale commercial farmers, hydro-electric power companies, other industrial users, municipal water users, and those using water resources for leisure and/or tourism. The complexity of different water users is associated with the complexity caused by different uses to which water resources are allocated, including irrigation, potable water, power generation, industrial production, environmental amenities, and recreation. The associated use and management rights are exercised through a variety of institutions that function at different scales. The governance structures for water resources management are often characterized by overlapping national, regional and local regulatory frameworks and authorities. Moreover, irrigation systems are typically common-pool resources and their management involves classical problems of collective action (see, e.g., Ostrom, 1990). There is a variety of mechanisms for allocating water resources, including administrative allocation, water markets and user-based allocation (Dinar *et al.*, 1997). Local water user associations play an important role in water resource management, and in many countries their role has been strengthened in recent years by decentralization and devolution (Meinzen-Dick *et al.*, 1997; Meinzen-Dick *et al.*, 2001). Moreover, negotiation approaches have gained increasing importance in water resource management (Bruns and Meinzen-Dick, 2000).

The last decades have seen increasing efforts to model the complexity of water resource management with the aim to use the model results for improved management (see, e.g., Jakeman and Letcher, 2003). In this paper, we highlight the development and use of a modeling approach that is particularly well suited to capture the complexities of water resource management described above: multi-agent simulation (MAS). MAS makes it possible to couple sub-models for water run-off, crop growth, economic decisions and network interaction within an integrated modeling framework. This is not a unique feature of MAS since there are a number integrated river basin models that have proven their ability to capture the technical, biophysical and economic complexities of water resource management. The specific strength of MAS, however, is that this modeling approach can also represent social and institutional relations among water users, enabling us to more fully capture social phenomena such as *collective action*.

To illustrate this modeling approach, we take a sub-basin of the Maule river in central Chile as an example (compare Figure 1 below). Chile is very well suited for a case study to show the potential of applying a multi-agent modeling framework for planning decision support. The country is internationally recognized for its innovative approach to water resource management. Chile has introduced a system of tradable private water rights and devolved the management of irrigation facilities to water user groups and their umbrella organizations. At the same time, public sector institutions have retained an important role in providing technical information and collecting data as well as in coordination,

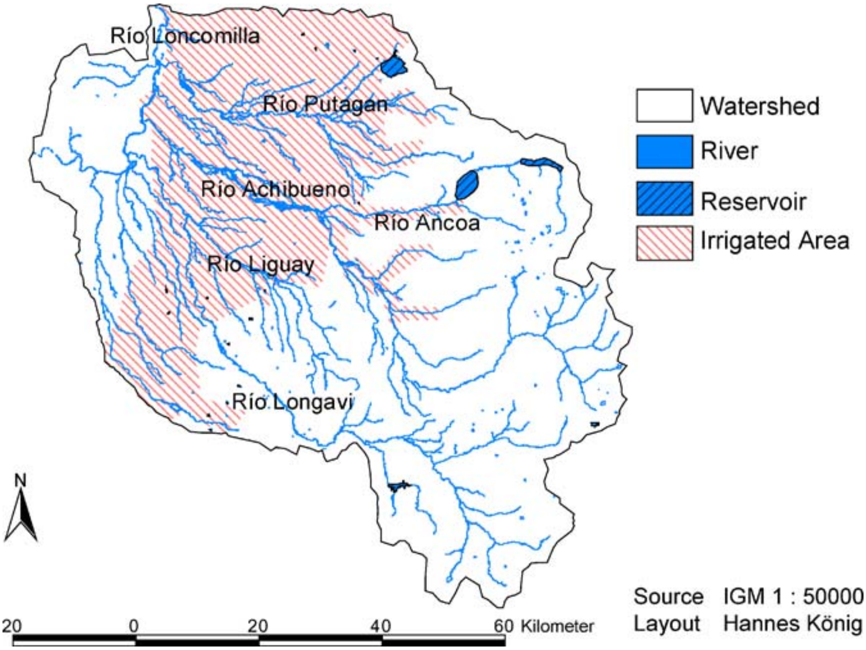

Fig. 1 Study area within the Maule River basin

oversight and conflict resolution. A new trend in water resource management is the privatization of large-scale infrastructure development in the form of concessions. The experience with the Chilean model of water resource management has, however, been mixed. For example, (Bauer, 1998) found that the market incentives to conserve water have been ineffective and that water right trading has been less active than expected. It is also an open question as to how marginalized water user groups in rural areas with low levels of political, bargaining and purchasing power will be affected by the next round of market-oriented management instruments. As we will argue in this paper, multi-agent simulation can provide an important planning tool which helps to better evaluate ex ante different policy scenarios and understand their implications for different groups of water users, including marginalized groups.

This paper reflects an early stage of research and focuses on the conceptual and methodological approach. It is the product of an ongoing research project within the "Challenge Program on Water and Food" of the Consultative Group on International Agricultural Research (CGIAR). The project aims at researching the practical use of a multi-agent simulation model in a multi-stakeholder context. Therefore the model is being developed and applied in a collaborative research and learning framework, which includes local water user organizations, state agencies, and local as well as international research organizations.

The paper proceeds as follows: Section 2 describes the study region. The problems for water resource management to be analyzed in this region are identified in Section 3. In Section 4, we describe the multi-agent simulation approach and its application to water resource management. Section 5 shows how the modeling approach will be applied in the study region. Section 6 concludes.

2. Background

The study area is located 300 km south of the country's capital, Santiago de Chile. The area consists of four micro-watersheds situated within the Maule river basin reaching from the central valley to the Andes pre-cordillera (Figure 1). The study area is mostly rural with favorable agronomic conditions, but due to the semi-arid environment agriculture is dependent on irrigation. The total area amounts to approximately 3,500 km^2 of which a third is currently irrigated (MOP-DGA, 2004).

The area produces high-value export crops in vineyards and fruit orchards, such as apples, grapes and raspberries, as well as vegetables for export and domestic markets. Sugar beet and tomato are mainly produced under contract agriculture, and traditional annual crops such as wheat, maize, beans, potatoes and other subsistence crops are grown for domestic consumption. The farm structure is heterogeneous and consists of modern large-scale export oriented enterprises, traditional hacienda type holdings that produce mainly wheat, sugar beet, and cattle, *campesino*[1] farm households that mainly received their holdings through the agrarian reform in the 1960s, and *minifundista* holdings. *Minifundista* and landless households often provide agricultural labor, especially for export crop production. Poverty levels compared to other regions in Chile are relatively high, according to the CASEN 2002 survey (*Encuesta de Caracterización Socioeconómica Nacional*).

Irrigation relies mainly on surface water resources and water availability varies considerably within years (extreme cases up to 20% from day to day) and between years (due to the phenomenon El Niño La Niña, which has lead to increasing rainfall variability). The irrigation infrastructure dates back to the 19th century; it has been erratically amended and the system is characterized by relatively low water-use efficiency. This is due to traditional irrigation methods, high levels of uncontrolled return flows, losses through infiltration, and lack of storage facilities for buffering overnight water flows. Beginning in 1981 with the establishment of a Water Code, Chile implemented a market-oriented approach to water resource management and assigned water rights to individual users. Water user rights are defined as shares of the total available water volume and tradable if registered. The poor infrastructure, however, makes monitoring of individual user's water uptake and water trade difficult.

2.1. Institutional set-up

Within the private water sector, water user groups are organized as follows: At the lowest local level users are organized in *Comunidades de Agua* (Water Communities); these groups are responsible for water distribution to users' plots, maintenance of tertiary and secondary irrigation channels, and the collection of fees for higher level organizations. The *Asociación de Canalistas* (Canal Associations) is the next highest level and comprises all those *Comunidades de Agua* that receive their water from one irrigation channel. They are responsible for the maintenance of this canal and distributing the water to the secondary canals that provide the water to the *Comunidades de Agua*. *Juntas de Vigilancia* (Watch Committees) are in charge of water distribution from a stream or reservoir to the primary channels. If smaller

[1] The category *campesino* comprises farm households that have land to employ the family members. They include beneficiaries from the Agrarian Reform but also farms in colonization areas and indigenous groups. *Minifundistas* hold too little land to employ the labor of their family and necessarily require off-farm income.

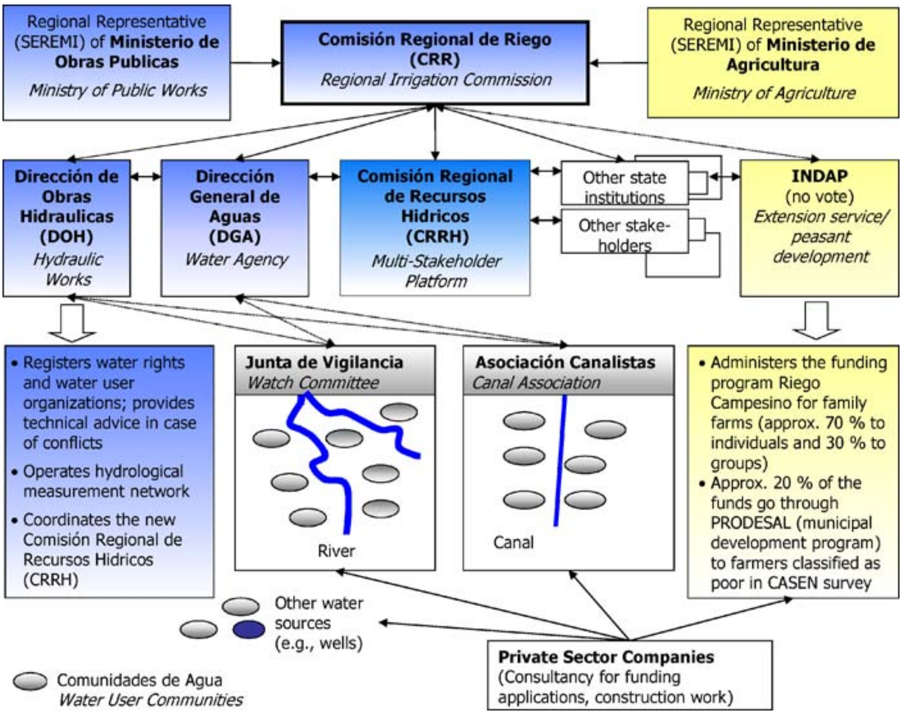

Fig. 2 Institutional set-up of the water sector at regional level

canals receive their water directly from a river or stream there is no intermediate level of an *Asociación de Canalistas*.

The most important surface water use besides agriculture in the 7th Region of Chile – the administrative entity pertaining to the study area – is hydropower generation. Currently there is no hydropower generation facility in the four micro-basins falling within the study area; however, concerns about the security of supply of natural gas from Argentina have increased the pressure to consider new hydropower projects. Conflicts between hydropower generation and irrigation mainly concern the timing of water release. Recreational use of water reservoirs currently occurs to a minor extent, but this may increase, especially in response to increased regional tourism. Another issue of increasing importance is water quality. The main concerns are poorly purified sewage water and contamination with agro-chemicals. Finally, the implementation of ‘good agricultural practices’ (EU-determined quality standards for high-value export crops) also has implications for both farming practices and water use and management. Certification to these standards has been a prerequisite for export to EU and US markets since 2002.

Within the public sector (Figure 2), there are two units belonging to the Ministry of Public Works (*Ministerio de Obras Públicas*) responsible for water management: The *Direccion General de Aguas* (DGA) and the *Dirección de Obras Hidraulicas* (DOH). DGA is in charge of registration of water rights and water user organizations and in charge of operating a measurement system for water flow. DOH is the technical counterpart in charge of the development of hydraulic infrastructure and of the maintenance of large-scale infrastructure such as reservoirs and bridges. Both entities, DGA and DOH, form part of the *Comisión*

Nacional de Riego (CNR), which is responsible for coordinating all irrigation related matters. At the regional level, the CNR is represented by the *Comisión Regional de Riego* (CRR) that supervises the application of the irrigation law (*Ley de Riego* 18.450) at the regional level. The CRR operates below the regional representation (SEREMI) of the Ministry of Public Works. The CRR is responsible for the distribution and administration of all public funds used in the irrigation sector. In November 2003, a regional commission consisting of the main stakeholders from the public and the private sector in the 7th Region, the *Comisión Regional de Recursos Hídricos* (CRRH), was created. The objective of the commission is to coordinate water uses and users at the regional level. The majority stakeholders of both surface and groundwater are included. Apart from the constitutional session, the commission has not met at the time of submitting this paper in January 2005.

The state supplies considerable funds to the irrigation sector for infrastructure development through different funding programs. As a general rule, users contribute 30% of investment costs. In principle, funds in all programs are attributed according to a competition process, which implies that the potential beneficiaries have to present projects to the state agencies in charge. These agencies evaluate the proposals according to the criteria specified for the relevant program. The final decision on these proposals is made by the *Comisión Nacional de Riego* (CNR). In this system, private consultancies play an important role because they formulate the technical dimension of the proposed projects. Poorer user groups may apply for state funds of the *Instituto Nacional de Desarrollo Agropecuario* (INDAP) and through regional and municipal institutions. However, in highly politicized procedures, municipalities and other authorities sometimes provide financing before or close to elections.

2.2. Market-oriented policy instruments

Although laid out in legal documents much earlier, it is only in the last four years that Chile has actually implemented market-oriented policies in infrastructure development; private concessions to the provision of large-scale infrastructure, and the transfer of existing infrastructure to water user groups. The first experience with concessions to infrastructure development is the Illapel reservoir (*El Bato*) in the 4th Region of Chile, which started in 2001 and was expected to be functioning in September 2004. The company that won the concession to build this reservoir received a state subsidy of about 75% of the investment costs to lower the price that water users will finally have to pay per cubic meter (Chileriego, 2001). Recently, the process of transferring existing infrastructure to water user groups also gained speed. A pre-requisite to these transfers is the legalization of the *Comunidades de Agua*, which is now extensively promoted by CNR and DGA. There is no general rule of how to transfer the infrastructure and how to share the costs. Depending on the socio-economic circumstances and other externalities, infrastructure can be completely transferred without any cost. In other cases, water user groups are asked to refinance the state-built infrastructure, or at least a certain share, which may explain why user groups are often reluctant to make these transfers, especially when rather old and poor infrastructure is to be devolved.

3. Problem statement

The complexity of water uses and users makes it difficult to manage water resources in an efficient and equitable way. Especially the second aspect, equity in access to resources and distribution of benefits, has not been investigated yet for the new market-oriented policy instruments in Chile. In this section, we present three policy research issues that will be analyzed with our multi-agent modeling system; trade of water user rights, development of small-scale infrastructure, and development of large-scale infrastructure.

3.1. Trade of water user rights

Even though trade in water is one of the theoretical advantages of Chile's liberalized water system, only one of the canal associations in the study region (Digua system) has so far developed the capacity to make this trade possible on a significant and regular basis. This leads to a number of policy-relevant research questions:

- What explains the differences across user associations in number of permanent and temporary transactions of water rights? Is trade hampered by poor infrastructure and monitoring facilities? Or are there only small potential gains from trade because of minor differences in water shadow prices of individual users?
- If there are indeed potential gains from trading of water rights, what are the most binding factors that restrict exploiting them more fully? Currently, short-term informal rental contracts are the most frequent form of water trading. What would be the implications of institutional innovations such as secured long-term rental arrangements?
- What is the nature and extent of externalities arising from trade of water rights? In one example, water users (Maitenes channel) report high infiltration losses in a secondary channel and insufficient water flows for irrigation because tail-end water rights were transferred and as a consequence less water flow was diverted into this channel.
- What are the distributional consequences of increased trade in water rights, particularly impacts on smallholders and farm laborers?

3.2. Development of small-scale infrastructure

Investment into and maintenance of small-scale infrastructure is a typical case of *collective action* problems at the lowest level of user organizations (here: C*omunidades de Agua*). Water users have to make individual contributions to jointly-used infrastructure; if a critical mass of users cannot be reached, joint-use facilities are never set up. Additionally, without effective collective action, existing facilities collapse because of lack of maintenance. Examples in the Chilean study region are canal maintenance and improvement, monitoring of individual water uptake and installment of measurement equipment, joint investments such as overnight storage, deep wells, and small-scale hydropower. This again poses a number of policy-relevant research questions:

- What are the incentives for individuals' to participate, given the extent of participation by others?
- What factors affect individual incentives, and what policies/mechanisms could be used to changes these incentives when they inhibit collective action? How are incentives to participate in one activity affected by collective action in other spheres?
- What factors at the water user association level appear to help or hinder collective action in any sphere? (e.g. heterogeneous interests, trust amongst community members, historical experiences)

3.3. Development of large-scale infrastructure

Planning of large-scale infrastructure projects, e.g. the two new multi-purpose dams of Ancoa and Longaví reservoir, involve interactions at higher levels of water user organizations. It is also not clear how the new market-oriented approach of giving out private concessions to build water infrastructure will affect holders of existing water rights versus new holders of additionally assigned water rights. Again, there are several research questions of policy relevance:

- What is the capacity of local user organizations to manage interactions with higher-level organizations and with government agencies? And during the planning process, what is the impact of information asymmetries on the concentration of assets such as land resources?
- How can competition between various water uses (here: hydropower, irrigation, and recreation/tourism) be reconciled in terms of quantity, timing, and quality? What are likely externalities for upstream and downstream water users?
- What are the likely distributional effects of private concessions in terms of access to water and poverty alleviation? Will new infrastructure projects improve the security of water supply for current holders of water rights versus newly assigned water rights?

Addressing these policy issues requires a methodological framework that captures both the complexity of multiple water uses and water users. In the next section we present multi-agent systems as a suitable modeling approach to accomplish this task and to provide policy-relevant information for planning decisions at local and regional level.

4. Multi-agent framework

In recent years much advance has been made in developing computational tools for planning decision support in water resource management. Most research efforts have been multi-disciplinary, for example down-scaling of global circulation models, coupling of meteorology/hydrology models (Kunstmann and Stadler, 2003) and integrated river basin models (Rosegrant *et al.*, 2000; Fischer *et al.*, 2002) to name a few. Integrated river basin models have been instrumental in capturing the complexity of water uses and highlighting the impacts of water reallocation across riparian countries and water-using sectors. These models, however, typically aggregate the categories of water use and do not capture the complexity of multiple water users within the different sectors (Berger and Ringler, 2002). As a result, they provide only broad and general insights for the ex-ante assessment of water management options at lower levels of user organizations. A new class of integrated computational models is therefore needed to explore distributional consequences of market outcomes, simulate corrective policy interventions, and prioritize funding of infrastructure projects.

4.1. Multi-agent systems applied to natural resource management

Here, we utilize a multi-agent system (MAS) model that couples water run-off, crop growth, economic decision and network interaction models at the water user level. MAS applied to natural resource management are generally implemented with fourth generation, object-oriented programming languages. They consist of two components; a cellular model component that links biophysical process models within a grid-cell framework, and an agent-based model component that links socio-economic decision and market models. Their specific characteristic is that all and each real-world actors are represented one-to-one by computational agents. MAS models have been applied to a variety of research questions (for an overview see Parker *et al.*, 2002; Janssen, 2002; Parker *et al.*, 2003), ranging from theorizing about social and spatial dynamics (Gotts *et al.*, 2003; Parker and Meretsky, 2004), simulating diffusion of innovations (Weisbuch, 2000; Berger, 2001; Deffuant *et al.*, 2002), land-use changes (Huigen, 2004) and agricultural policies (Happe *et al.*, 2004), to accompanying role-playing games (Barreteau *et al.*, 2003) and game theory applications (Bousquet *et al.*, 2001).

Of particular importance for this study are *empirical MAS* that are based on empirical data and used for policy analysis (see for example Berger *et al.*, 2006). New statistical approaches are required for the empirical parameterization of these models; common sampling frames that hierarchically link observation units and guide biophysical field measurements and socio-economic surveys (Van de Giesen *et al.*, 2006) along with Monte-Carlo techniques for generating agent populations from sample data (Berger and Schreinemachers, 2006).

4.2. Model specification for case study

The MAS model specification for the case study reported here builds on earlier work of (Balmann, 1997; and Berger, 2001). The model is recursive/dynamic and is used for comparing alternative policy-planning scenarios (simulation horizon 15 to 20 years). It is coded in C++ and runs on Windows and Unix/Linux platforms.

The cellular model component consists of the following sub-models (Figure 3):

1. WaSiM-ETH for the simulation of water flows and balances at micro-watershed level (resolution 100 m, daily time steps). Inputs required are meteorological data, a digital

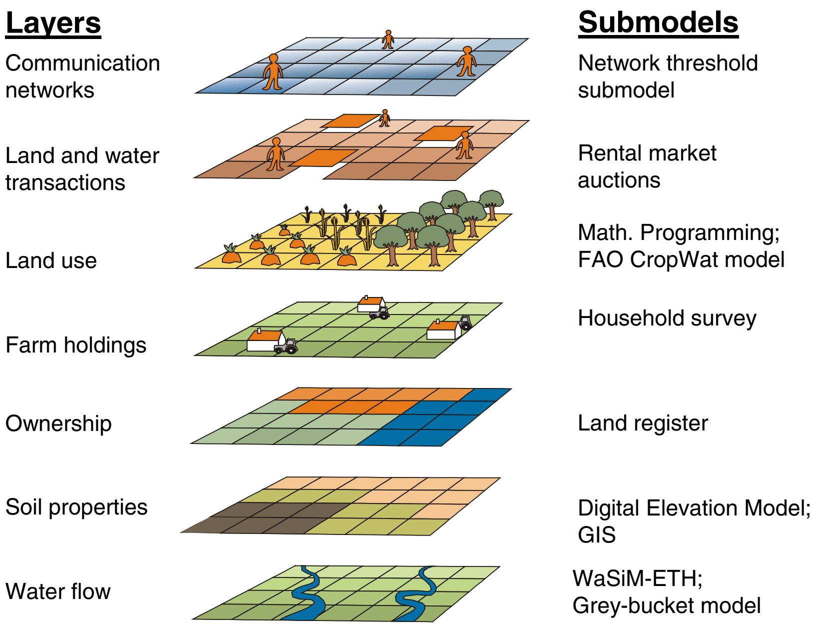

Fig. 3 Components of the Multi-Agent Simulation Model Layout C. Block, ZEF-Bonn. First published in Berger and Ringler (2002)

elevation model and gridded information on soil properties and land use (Jasper *et al.*, 2002).

2. A digital elevation model and GIS coverages such as water infrastructure, location of farmsteads and parcels (taken from land register), soil types (USDA classification), and land cover (Landsat satellite images). Data from field measurements and socio-economic surveys was geo-referenced and incorporated into the database.
3. A grey-bucket model for the diversion of irrigation water within irrigation sections (here: *comunidades de agua*), building on a water-engineering study for the Chilean Ministry of Public Works (see model equations in Berger, 2000). This model will be calibrated with run-off measurements during the peak irrigation season.
4. A crop growth model building on the CropWat model (FAO, 2005), calibrated to regional conditions (about 180 cropping activities including fruit and forestry plantations). Technical coefficients such as labor and fertilizer inputs are being collected from the project's farm holding survey complemented by farm trial data of the University of Talca and INIA (*Instituto Nacional de Investigación Agropecuaria*).

   The agent-based model component consists of the following submodels (see detailed description in Berger, 2001; listing of parameters and equations in Berger; 2000):

5. An agent planning and decision model implemented as a sequence of mixed-integer mathematical programming problems (MIPs). The IBM-OSL runtime library is used for solving these problems. The model agents may either represent (a) single water users such as farm households, or (b) the aggregate of all users within one water-using sector. In case (a) recursive MIPs for each and all agents are solved for all years over the simulation horizon, allowing for interactions between them. In case (b) the model specification is equivalent to integrated river-basin models and used for 1 year comparative-static simulation experiments.
6. Transactions of land and water resources are implemented as local auctions submodels. A rental market mediator compiles a list of parcels for renting out and then asks for bids of all potential tenants (bids based on shadow prices, considering the transport costs (distance) between the offered plot and the tenant's farmstead). Provided the highest bid is larger than the landowner's asking price (computed as the incremental return when renting out this parcel), the price is fixed as the average of asking price and highest bid, and the transaction takes place.
7. A network threshold submodel captures the interaction of agents in communication networks. Innovation information, for example about the adoption of water-saving irrigation techniques, is typically exchanged among members of distinct social networks. The position of a particular human actor in these networks can be empirically measured by its network threshold, defined as the percentage of all other peers within its reference group that must previously engage in a novel activity before the actor eventually adopts this behavior. The network submodel is implemented as follows (for details see Berger, 2001): model agents monitor the present adoption level of an innovation and compare it with their individual threshold. If their threshold is reached, they evaluate the innovation and calculate the farm's net benefits from adoption. If the net benefits are positive, they adopt and thereby increase the adoption level monitored by other network members.
8. A critical mass submodel that captures collective action problems of water users within local level user associations, for example maintenance of and water uptake along secondary and tertiary irrigation channels. Model agents form expectations about the other agents' initial dispositions to cooperate and monitor their behavior. Depending on the distribution of incentives over agents the critical mass of cooperating users may not be reached, which in turn would lead to collapse of the maintenance and monitoring systems. Under such

circumstances the MAS model allows to test policy interventions that give sanctions and/or additional incentives to foster cooperative behavior of agents.

Note that comparing the case (a) and (b) specifications of the agent planning and decision submodel (see point 5 in list above) provides useful insights for policy analysis. Case (b) represents the optimal water allocation aggregated over all water users in the absence of information and transaction costs. This optimal solution based on pooling of resources accordingly quantifies the potential gains from a perfectly coordinated allocation of water among multiple uses and users. Disaggregated case (a) scenarios compared against this benchmark indicate the magnitude of information and transaction costs. Simulation experiments would then help to identify the most binding constraints to exploiting these potential gains (see for more details Berger and Ringler, 2002).

4.3. Preliminary simulation results

In the following we present some preliminary simulation results which show the type of quantitative information generated by the MAS. Since the socioeconomic surveys are under way and some of the model components are still under construction – for example WaSiM-ETH and updated GIS coverages –, we used the model specification and data from (Berger, 2001) to analyze the dynamics of water trade, water user income and water use efficiency in the study region. Under the current institutional setting, as mentioned in Section 3, water trade is almost exclusively done informally and on a short-term rental basis. The rental payment is typically due at the beginning of the one-year contract, and the tenant assumes the uncertainties related to actual on-field water availability. Such rental arrangements, therefore, provide only small incentives to the tenant to adopt technical innovations such as high-value permanent crops and new water-saving irrigation techniques. We would therefore expect a very limited effect of water rental trade on water user incomes and water use efficiency. The MAS is used to quantify this effect vis-à-vis the underlying dynamics of technical change in the study region. Again, the simulation results here are preliminary since they are based on data available in 1997 (for a discussion of model validation see Berger, 2001).

Figure 4 depicts the effects of technical change on average household income and on on-field water use efficiency (for details of the technology adoption model see Berger, 2001). Ideal technical change – ideal means here the diffusion of innovations occurs without any adoption costs – could almost double the average household income, compared to the hypothetical situation without innovation. Average water-use efficiency would then considerably improve within a few years and reach a maximum level of about 45%. But under market conditions, the simulation experiments suggest only modest increases of income and water-use efficiency. Household incomes are likely to increase by 11%, compared to the situation without innovation, and water use efficiency may reach a maximum level of about 30%.

The MAS provides further insights into the impacts of current water trade arrangements. We undertook a series of simulation experiments to quantify the likely effects of both technical change and rental markets, which are summarized in Table 1. To isolate the effect of rental markets we either switched the auction module off (first column for each indicator) or on (second column for each indicator). First, note that the scenario ‘market solution’ in row #2 and column #2 replicates the observed level of rental activities of about 11% (see Berger, 2001). Second, we see rental activities decrease the more households are reached by technical change. Third as column #3 and #4 show, rental markets have a relatively large effect on the average household income. The average household income would drop by about 13%, compared to the baseline scenario with rental markets and without technical change. The

Table 1 Simulation experiments on the impacts of informal rental markets

Values in percent rental markets	Rental market activity		Incremental household income		On-field water use efficiency	
	No	Yes	No	Yes	No	Yes
Ideal technical change	0.0	2.8	78.4	80.4	43.0	42.7
Market solution	0.0	11.5	−13.5	11.0	26.3	28.4
Without technical change	0.0	13.1	−13.5	0.0	26.3	25.3

Notes. Preliminary simulation experiments based on data of 1997. Rental market activity is measured as the percentage of transferred water/land resources per year. Incremental household income refers to the discounted increase of average household income (“Net Benefit Increase”), compared to the baseline scenario (rental markets – without technical change)

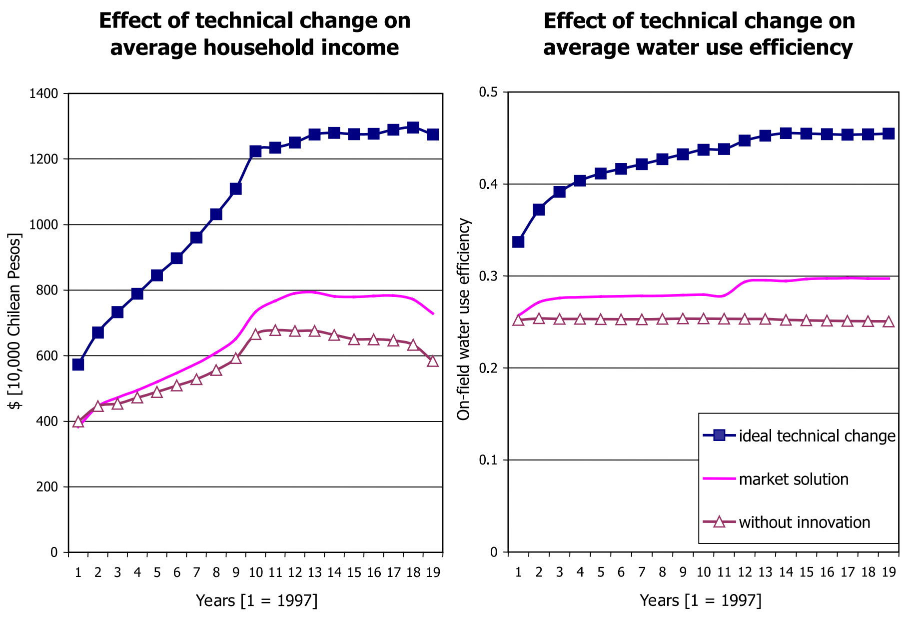

Fig. 4 Simulation experiments on the impacts of technical change

reason is that farm households that are not reached by technical change engage in off-farm activities and even opt for out-migration, which in turn increases supply on the rental markets. However, under the current water trade arrangements, this re-allocation of water/land resources has had rather limited effects on on-field water-use efficiency, as columns #5 and #6 show.

In summary, the simulation experiments highlight the large potential from technical innovation but the limited potential from water trade under current rental arrangements.

5. Outline of simulation approach

In Section 3, we identified three policy relevant research questions; trading water rights and the development of small-scale and large-scale infrastructure. In this section we outline how MAS can be used to address these research questions. This section is divided in five sub-sections. The first sub-section characterizes the collective action problems that are inherent in water resource management and that can be analyzed using MAS. In the second to fourth sub-sections, we specifically discuss collective action problems that may arise in water trading and in small-scale and large-scale infrastructure provision, respectively. The final sub-section describes the collaborative research and learning framework that is being established for the use of MAS.

5.1. Collective action problems in water resource management

As indicated above, the specific strength of MAS is that the model can represent social and institutional relations among water users, enabling us to more fully capture social phenomena such as collective action. And, the nature of the model lends itself to continuous process two-way information flows (user-model-user). Both of these characteristics are extremely important in the development of a planning support tool in the complex institutional environment operating in Chile, where irrigation infrastructure is (often) jointly used and managed, and thus must be jointly maintained and monitored. Such jointly used goods require collective action since all users benefit from a well-maintained irrigation system; however, individuals may not fully provide the public goods and services required for optimal investment and maintenance. This situation constitutes a so-called social dilemma. To solve such dilemmas game theory has made important contributions (for specific reference to public goods provision, c.f. Cornes and Sandler, 1986; Sandler, 1992). Nonetheless, analytical representations of game-theoretic models often lead to ambiguous results, particularly when there are many heterogeneous agents, stochastic parameters, etc. The latter means that empirical data to support parameterization of the model is critically important.

In terms of collective action and the functioning of the irrigation system, there are three critical aspects to consider. The first is characterizing the (different) individual incentives to undertake any given collective activity, given the institutional rules and transactions costs for undertaking collective action. Using MAS, we can capture these incentive structures, determine how changes in various external parameters alter these incentives, and thus develop well-defined and targeted policy options to change these incentives and thus promote collective action. Secondly, we can empirically evaluate the transactions costs of collective action at the level of local water-user associations, and also determine how changes in local institutional rules and mechanisms can alter individual incentive structures. Third, we can evaluate links amongst different stakeholders throughout the system, including those between local level water user associations to higher level irrigation agents, between current rights holders and those who may gain from new rights, and between stakeholders representing very different interests in use, e.g. irrigation, hydro-electric power, and recreation.

While the general institutional framework of water use in Chile has been briefly described in Section 2 of this paper, in the next section, we outline more clearly different types of collective action problems that may arise within the context of trading water, development of small-scale (local) water infrastructure, and development of large-scale (supra-local) infrastructure. Though incorporating the institutional framework determining the extent of collective action into the MAS model remains our most important future activity related to data collection, in Section 5.2, we present an illustrative example of the distribution of net gains arising from the discrete decisions to invest in water flow monitoring equipment; space constraints prevent us from doing the same for sections 5.3 and 5.4 here.

5.2. Collective action problems in water trade

We first consider aspects of water trade that imply a potential role for collective action. An important condition for the emergence of trading in water rights is that the purchasers of these rights are assured that they will indeed receive the water in accordance with the rights purchased. In cases where water flows from all primary, secondary and tertiary canals are monitored using sophisticated water flow measurement equipment, the development of water trading rests on the enforcement of water rights using the information collected; the technology provides the information needed for enforcement and there is little need for collective action. Even under this system, however, negative asymmetric externalities may be generated which affect those not party to the trading itself. For instance, if there is a concentration of a significant number of users renting out their rights in some part of the system, this may alter the flow of water throughout the system thereby affecting other users (see Section 3). Avoiding this type of negative externality requires an understanding of the entire irrigation system, and thus a forum where different users can acquire this information and negotiate new rules regarding transfers.

Where information on distribution is not monitored with equipment, collective action and coordination activities become more important. Consider first trading of rights within the same water user organization. If everyone with rights believes that the distribution system functions well enough in the sense that they indeed receive their share of water, then it may be a simple matter to trade water rights. Even in this case, however, community members as a whole must "support" this trade in the sense that, with traded rights, members do not change their behavior compared to the no-trade (or less trade) situation. If the current "no-trade" system functions because near-neighbors monitor each other's use, then a downstream user considering the purchase of an upstream user's water allocation must be assured that the *seller* will still monitor his/her neighbors' use. Yet, the incentives for the seller to provide monitoring, particularly if payment is made at the beginning of the season, are reduced vis-à-vis the situation where monitoring is necessary to ensure that one's own allocation is received. This monitoring problem can be expected to be reduced to the extent that a seller wants to have the option to rent out rights in the future as well. However, the larger the distance between the purchaser and the seller, the greater are the chances that others not involved in the contract become tempted to take a little bit more, since more water is flowing through. To offset this, someone – most likely the purchaser – will have to increase monitoring.

The monitoring and enforcement problems become even more severe when trading occurs across different communities of water users. Though representatives of community water user associations can attend meetings at the next higher level of aggregation (*Asociación de Canalistas* or *Junta de Vigilancia*), there is often no formal framework for negotiating trades.

A simple example may help to illustrate the information on incentives that will be generated by the model. Consider a simple 6-person game, where the players choose whether or not to invest in water flow monitoring equipment. Additionally, assume that, without the new equipment no trades are made. Each individual then chooses between two options: either to not contribute or to make 1/Nth of the total contribution required. If all do not contribute their share, contributions are returned at no cost. Players differ only in their productivity of water use, with player 1 having the highest productivity, and player 6 the lowest.

Player 1	Players 2:6: All Contribute	Players 2:6: None Contribute
Not Contribute	2804, [411- 2403]	1877, [7- 1551]
Contribute	1877, [7- 1551]	1877, [7- 1551]

Fig. 5 Payoff matrix, investing in water monitoring equipment, Player 1 and Players 2:6

The payoff matrix shows the gains from either contributing or not contributing (Figure 5). Returns to player 1 are always in the first place in each column; for simplicity, we have summed the returns to players 2–6 into one grand "player", and shown the returns to contributing and not contributing for this group as a whole. Underlined returns show the "best response" of each player to the action of the other; the grey cells indicate the two equilibrium of this game. As we can see, there are two equilibria: either all contribute or none contribute; a standard result for a discrete investment decision. In this particular case, the incentives to cheat – the difference between all contributing vs. all contributing except the player in question – are in fact negative (and equal to negative net gains). Incentives to not be taken advantage of–the difference between no one contributing and the player contributing when no one else does–is equal to zero, since contributions are returned costlessly if not enough funds are raised.

Figure 6 illustrates total net gains to each player if the investment is made, under two different scenarios: the first where the fixed investment cost per member is \$100, and the second where the investment cost is \$200. Though extremely simplified, the Figure 6 highlights two interesting concepts. The first, well-known to trade theorists, is that gains to trade are the greatest for the most and least efficient under both scenarios. Second, while in both scenarios all players find it in their best interest to contribute, the total amount of water traded and total net benefits decrease. If fixed investment costs rise just a bit more, Player 4 will lose money by making the required contribution; and if a strict per person payment system is enforced, the investment will not be undertaken. In other words, it is the "medium" efficiency group that will gain least from trading. Heterogeneity implies that a simple per person charge is less likely to lead to investment; and intra-group bargaining over the investment payment schedule will then ensue. On the other hand, if each member is allowed to choose how much to contribute, then a sub-group may form to provide the investment in any case; here, we would expect both the least and most efficient water users to pay the greatest amount.

5.3. Collective action problems in small-scale infrastructure provision

The second research question addresses development of small-scale infrastructure, such as the purchase and installation of water distribution monitoring equipment, overnight water storage facilities, and the maintenance of secondary and tertiary canals. As discussed above, investing

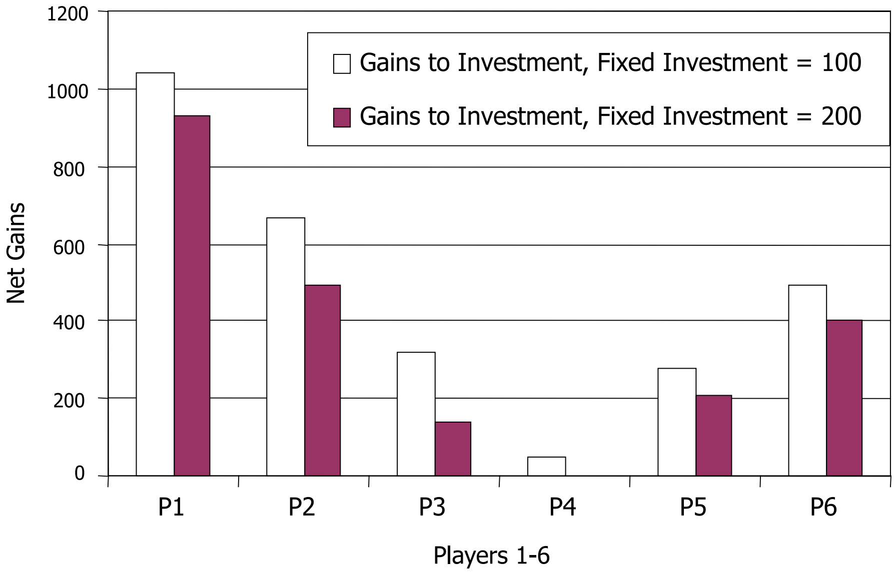

Fig. 6 Net gains from investing in water monitoring equipment and subsequent trade

in water distribution monitoring equipment provides information on actual quantities of water used by each member; such information provides a pure public good even in the absence of water trading. The discrete decision to invest in storage facilities has similar characteristics to the decision to invest in water monitoring equipment.

Additionally, most irrigation investments require periodic maintenance at both the household and community level. Water users must make agreements on maintenance activities, assign responsibilities, and monitor and enforce these agreements. Monitoring maintenance contributions may well be more costly than ensuring everyone contributes their share to a specific investment. In the case of discrete investments described in Section 5.2, as long as net gains to the investment are positive, then there are no incentives to free-ride (in fact, there are "negative incentives"), and no incentives to not be taken advantage of. In the case of maintenance, where each additional unit of labor or money has a marginal impact on the condition of the canal, there are likely to be both incentives to free-ride, and incentives not to be taken advantage of, even when there are net gains to all if all contribute their share. Figure 7 below illustrates a 2 player payoff matrix illustrating this potential outcome.

Fig. 7 Payoff matrix, contributing to canal maintenance, 2 Players

		Player 2	
		Contribute	Not Contribute
Player 1	Not Contribute	2000, 2000	1700, 2100
	Contribute	2100, 1800	1800, 1800

As with the discrete investment decision, players are indeed better off if all players maintain the canal, but unlike the investment decision, there are now both incentives to free-ride as well as incentives to not be taken advantage of. This result, a “prisoner’s dilemma”, often occurs with continuous decisions where inputs exhibit diminishing returns and costs expended can not be “returned”. In these cases, then, policies or rules need to be constructed that both assure each member that all will contribute (reduce the losses that can occur if you contribute but no one else does), and that reduce your incentives to free-ride (decrease returns to free-riding by selective punishments, for instance).

As with water trading, the MAS model can be used to generate the payoff matrices that characterize the maintenance and investment environment, the distributional consequences of existing investment and maintenance activities, the change in net benefits due to changes in the external environment, and thus the types of policies and/or institutional mechanisms that can be used to alter incentives that currently hinder maintenance and investment.

5.4. Collective action problems in large-scale infrastructure provision

In case of large-scale infrastructure, such as large reservoirs, the investment will affect a much larger group of users than those comprising a water user association and it will often affect users other than farmers, such as hydro-electric power plants, industry, tourists, and municipal authorities. Large-scale infrastructure projects often generate positive externalities, such as a less fluctuation in water flow and new tourism potential, but may also generate negative externalities, such as reduction of biological diversity. Reconciling different water demands will be a much more difficult task, and will require some type of institutional structure within which negotiation and bargaining can take place. The different groups involved may differ in their abilities to organize and articulate their interests, which constitute an inherent problem for bargaining and thus a key role for collective action, especially among resource-poor constituents.

Apart from these local collective action problems, the provision of large-scale infrastructure also involves a number of other problems. For example, the relation between established political decision-making processes and platforms, some created specifically to increase involvement of “all” stakeholders, needs to be clarified in order to capture the distribution of bargaining power and capacity of different stakeholders to shape certain institutional rules. As discussed in Sections 2 and 3, privatization is an option high on the current political agenda. The privatization of large-scale infrastructure provision, based on a concession system, creates additional challenges for decision-making, and for ensuring that public interests are assured.

The MAS can be used to simulate the effects of different types of institutional arrangements for provision and management of large-scale infrastructure. For example, MAS can be used for assessing the effects on all users of giving seasonal priority to hydropower. The MAS can also show the incentives for a private firm to invest in the provision of large scale infrastructure such as reservoirs to increase the amount of water stored. The MAS can also generate different shadow prices for water, thus showing were new water rights might receive the highest prices as well as calculate the distributional effects among the different users. Thus, the effects of different terms of concession contracts can be simulated.

5.5. Collaborative research and learning framework

The main goal of the research project is to develop a modeling system that is of practical use for decision makers faced with the collective action problems identified above. An important prerequisite for being able to provide decision support in practical planning processes is to reach a state in which the different stakeholders have trust in the model and its simulation results. The MAS has a distinctive feature that facilitates trust building. Since the model depicts specific agents, it is easier for model users to identify themselves with these agents and the way in which their behavior is modeled than to understand or trust a set of differential equations.

In the case study under consideration, a collaborative research and learning framework has been set up to provide a platform where the MAS can be developed jointly with those interested in using it. This approach is expected to promote ownership and build trust in the model. The joint development has three objectives: (1) to improve the quality of information used to set up and parameterize the model, (2) to ensure that the relevant questions and criteria can be addressed with the model as well as to identify relevant and feasible policy options and (3) to provide decision makers with access to the model which ideally includes training them to use it.

In order to identify the most appropriate counterpart institution for this joint development, an analysis of the existing governance structures involved in irrigated water use and management was conducted as a first step of the research project. Using information from the governance structure analysis, a stakeholder needs and priorities analysis was undertaken, to ensure that the interests of various stakeholders will be captured by the MAS model. Additional economic and institutional data required to generate parameters to baseline the model are being collected by means of a household survey, a survey at the level of the leaders of the water user associations, focus group interviews within the communities, and key informant and expert interviews at these and higher levels.

6. Discussion and conclusions

The case study presented in this paper shows that multi-agent simulation has a considerable potential for providing planning decision support to policymakers and stakeholders. We identified three areas of water resource management, where MAS can make particularly useful contributions: trade in water resources, small-scale infrastructure and large-scale infrastructure provision. Each of these areas is characterized by specific bio-physical, technical and socio-economic problems. While the bio-physical and technical aspects of multiple water uses are generally well studied and analyzed with existing model approaches, capturing the collective action problems of multiple users and their socio-economic implications in these three areas constitutes a major challenge.

We have argued for each of these three management areas that MAS has a comparative advantage in dealing with this challenge, because it makes it possible to represent and disentangle the diversity of real-world actors and their interrelations. Game theory can be combined with MAS to model the behavior of these actors. Testing different behavioral assumptions and pay-off matrices allows the analyst to gain insights into the underlying distribution of incentives and the dynamics of collective action problems, and to determine how cooperative outcomes may be encouraged by additional policy instruments.

The fact that multiple actors can be included in the model makes it possible to place emphasis on distributional effects of market-oriented policy instruments that may be overlooked otherwise. For example, the implications of infrastructure development for poor and disadvantaged sections of the rural population can be modeled explicitly. Likewise, complex environmental consequences can be better understood and considered in the planning process.

A distinctive advantage of MAS is that it specifies the trade-offs involved in different scenarios, thus allowing policymakers to make better informed decisions. By providing information to the public, the use of MAS may also increase transparency, which is an important aspect of good governance.

The use of MAS also involves challenges which will be briefly discussed here. A major challenge is to ensure the sustainability of using MAS in practical planning situations. Since the model is intended to be used in a multi-stakeholder setting, there are considerable social and management skills required to handle such model-enhanced planning processes (Paassen, 2004). Therefore, there is a need for constant learning and capacity building in the institutions developing, maintaining and using the MAS. As indicated above, another major challenge is to ensure that the stakeholders and the political decision-makers build trust in the model and its simulation results. Since the use of an MAS does not in itself change existing power structures, efforts have to be made to avoid the "capture" of the model by more powerful stakeholders, who may, for example, influence the choice of the scenarios that are – and are not – modeled. Another challenge of this approach is the need for multidisciplinary cooperation between members of various natural science and social science disciplines (Berger *et al.*, 2006). There is also a need to establish an interface for different types of knowledge, including local knowledge and scientific knowledge. This involves communication challenges and requires a learning process that is not trivial. In conclusion, we hope to have shown in this paper that the potential offered by MAS justifies facing these challenges.

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