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Feedback mechanisms between water availability and water use in a semi-arid river basin: A spatially explicit multi-agent simulation approach

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ABSTRACT

Understanding the processes responsible for the distribution of water availability over space and time is of great importance to spatial planning in a semi-arid river basin. In this study the usefulness of a multi-agent simulation (MAS) approach for representing these processes is discussed. A MAS model has been developed to represent local water use of farmers that both respond to and modify the spatial and temporal distribution of water resources in a river basin. The MAS approach is tested for the Jaguaribe basin in semi-arid Northeast Brazil. Model validity and required data for representing system dynamics are discussed. For the Jaguaribe basin both positive and negative correlations between water availability and water use have been encountered. It was found that increasing wet season water use in times of drought amplify water stress in the following dry season. It is concluded that with our approach it is possible to validly represent spatial-temporal variability of water availability that is influenced by water use and vice versa.

1. Introduction

This paper discusses the applicability of a spatially explicit multi-agent simulation (MAS) approach to represent the dynamics of water use for irrigation and the effect it has on spatial and temporal water resources distribution across a semi-arid river basin. The geographical locations of water users and the timing of water use influence temporal and geographical distribution of water availability across a basin. In this study the feedback relation between water availability and water use under influence of rainfall variability is essential for system dynamics. Water use in the irrigation sector is of significant importance to water availability in the Jaguaribe basin (Van Oel et al., 2008). There is a feedback relation between water availability and water use which is influenced by rainfall variability. Obviously, water use subtracts from water availability but the effect of water availability on water use is less straightforward. By the use of MAS this relation is further explored as the rationale of individual water users that respond to variations in water availability in different seasons can be taken into account. Interventions in the natural course of water in one place influence water availability and water use in that place itself, as well as in other locations. Obviously, higher water demands lead to increasing water use and therefore reduce water storage levels. Conversely, water storage influences demand for irrigation water, because users anticipate and respond to water availability by modifying their decisions on the area of land to be irrigated and the type of crop to grow.

A MAS model for the spatially explicit depiction of resource use consists of a spatial model, either grid-based or polygon-based, generally representing geophysical aspects of a natural resource system and an agent-based model representing human decision-making that is related or relevant to the system. It is increasingly acknowledged that multi-agent simulation is an adequate modelling technique to represent human–environment interactions (e.g. Barthel et al., 2008; Bithell and Brasington, 2009; Bousquet and Le Page, 2004; Doglioni et al., 2009; Filatova et al., 2009; Matthews et al., 2007; Parker et al., 2002, 2003; Verburg, 2006; Yu et al., 2009). MAS models may help to portray systems in which interdependencies between agents and their environment are essential to the proper understanding of system dynamics where the heterogeneity of agents or their environment critically impacts model outcomes and where adaptive behaviour at the individual or system level are relevant for the system under study (Parker et al., 2003). According to Matthews et al. (2007) different applications of MAS models for land use are designed to serve one or more of the following five purposes: (1) policy analysis and planning; (2) participatory modelling; (3) explaining spatial patterns of land use

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or settlement; (4) testing social science concepts; and (5) explaining land use functions. With regard to policy analysis, Berger et al. (2007) show that MAS is a promising approach to supporting water resource management and to better understanding the complexity of water use and water users within sub-basins. Schlüter and Pahl-Wostl (2007) developed an agent-based modelling approach to compare alternative water management regimes. It enables the resilience of a social–ecological system with respect to uncertainty and changes in water availability in Central Asia to be studied. This study intends to explore the effects of water use for irrigation in a semi-arid environment on water availability distribution and vice versa. The approach aims at model outcomes that are relevant to policy analysis and spatial planning, as well as explaining spatial patterns of water use and water availability. To test the approach the Jaguaribe basin in the semi-arid northeast of Brazil was studied.

In the study area there are strong dependencies between water users at the basin level with respect to water availability (Van Oel, 2009; Van Oel et al., 2009). For the assessment of reservoir yield it was found that including upstream water use for irrigation significantly improves the accuracy of predictions (Van Oel et al., 2008). As for land use models (Verburg, 2006), the inclusion of feedback mechanisms between water availability and water use requires new methods of model parameterisation and calibration and will ultimately increase our understanding of resource system dynamics. In this study we explore whether the use of MAS modelling, including agents equipped with simple decision-making heuristics based on empirical survey data, is helpful in representing system dynamics that contribute to the distribution of water availability in a semi-arid river basin.

2. Method

2.1. Model description

The ABSTRACT model (Agent-Based Simulation Tool for Resource Allocation in a CatchmenT) is designed for a basin or sub-basin in which surface water storage reservoirs have been built and the irrigation sector is an important water user, and in which there are possibilities for multi-annual water allocation management. To represent human–environment interactions a multi-agent simulation (MAS) approach is adopted. The ABSTRACT model is developed with the CORMAS platform under the VISUALWORKS environment (Bousquet et al., 1998). To represent feedback processes between water availability and water use for irrigation, system components related to topography, hydrology, storage and water use for irrigation are included. These four aspects are strongly related and representing their interaction is done in a spatially explicit cellular model environment. Out of many possible model outputs, the main focus is on analysing the spatial distribution of water availability and water use.

Agents represent farming households that are situated at specific geographical locations and make decisions, followed by actions, affecting the environment. The modelling sequence is as follows: (i) physical parameter update; (ii) biophysical dynamics; (iii) land use decisions and actions; and (iv) land availability update. In the physical parameter update rainfall and upstream inflow are realised. This is done at the beginning of every 10-day time step. The biophysical dynamics involve crop growth and water balance calculations of agricultural fields and, alluvial aquifers and surface water reservoirs. Decisions on land use are made by individual farmer–agents, taking into account local conditions and preferences. These decisions are followed by actions implementing them. Harvesting takes place when crops are ready to be harvested, or harvests are lost by flooding. At every time step land availability is updated according to water levels in reservoirs and land cover changes due to harvesting.

Within the CORMAS platform several object classes are generated in which methods are implemented to represent system dynamics. A spatial entity class, represented by one grid cell, corresponds to a *Plot*. There are two agent classes: *Farmer* and *Allocation Committee*. *Farmer*–agents decide on land use and water extractions from surface water or groundwater sources, while *Allocation Committee*-agents decide on reservoir releases. Geographically located object classes are: *Crop*, *River* (branch) and *Node*. River branches connect *Nodes* and can contain storage, through either an *Alluvial Aquifer* or a surface water storage *Reservoir*. Fig. 1 shows the main model classes and the names of their main attributes and methods. Water balance operations of agricultural fields are modelled in the *Plot* and the *Crop* classes. The water balance of alluvial aquifers and surface water reservoirs is arranged in the *Node* class and its subclasses.

2.2. Water balance

A semi-distributed hydrologic modelling approach is used. The river is represented by a sequence of branches, each of which depicts a part of the river including its underlying alluvial aquifer. From each branch water is withdrawn and water returns from riparian areas. Among these are irrigation areas that consist of grid cells for which a water balance is simulated. Water balance calculations take into account the soil and crop characteristics that are listed in Table 1. Each branch receives water from its upstream river branch or branches and from riparian grid cells that provide runoff and return flows from irrigation. Water storage is arranged in alluvial aquifers and reservoirs, depending on local circumstances. The representation of the water balance is schematised in Fig. 2.

To determine the water demand by farmers in irrigation areas a modelling approach that is designed for a 10-day time step (Perez et al., 2002) is implemented in CORMAS in the same way it was implemented for the CatchScape model that was developed by Becu et al. (2003). Use is made of data on soil parameters and crop parameters for all grid cells. External data are provided for rainfall (P) and potential evapotranspiration ($ET0$) values. At each time step the water balance of a grid cell can be expressed as a mass conservation equation (all units in m^3/s):

$$\frac{\Delta S_{\text{cell}}}{\Delta t} = P + I - R_S - R_{SS} - \text{ET} \tag{1}$$

where ΔS_{cell} is the change in actual soil water storage over a time interval Δt, P is rainfall, I is water used for irrigation extracted from an irrigation source, R_S is surface runoff, R_{SS} is sub-surface runoff, and ET is actual evapotranspiration. In this way grid cell-specific water demands for irrigation (I) can be determined at every time step. In the simulation a time step of 10 days is used.

The water balance of a river branch, including the underlying alluvial aquifer, can be expressed at each time step as a mass conservation equation (all units in m^3/s):

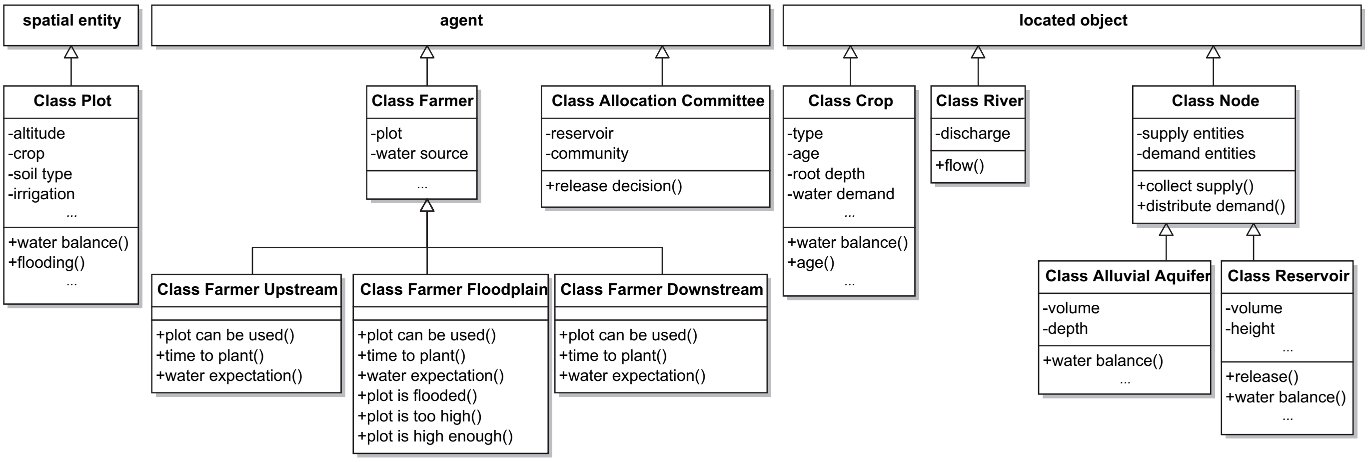

Fig. 1. Class diagram of the ABSTRACT model.

Table 1
Parameters and data requirement of the ABSTRACT model.

Model parameters	Unit
Meteorological parameters	
- Precipitation	mm
- Number of rainy days	Number of days during the 10 day time step
- Potential evapotranspiration	mm
Soil characteristics	
- Soil depth	mm
- Daily infiltration rate	mm
- Total available water (in mm/m)	mm/m
- Water available for evaporation	mm
- Water readily available for evaporation	mm
Crop characteristics (Doornbos and Pruit, 1977)	
- Four vegetative period durations (L_{ini}, L_{dev}, L_{mid}, L_{end})	days
- Three crop coefficients (KC_{ini}, KC_{mid}, KC_{end})	–
- Initial root depth	mm
- Final root depth	mm
Water system data	
- Discharges of upstream inflow (only if the area is not an isolated catchment)	m^3/s
- Reservoir releases and surface–volume relationships	m^2/m^3
- Digital elevation model	m, suitable for a 270 × 270 m grid
- Runoff coefficients	–
Farmer-agent decision rules	
- Preferences for rainfall quantities	mm
- Availability of water in sources for irrigation	m^3
- Crop preferences given the quantities of rainfall and available water in sources for irrigation	e.g. rice, maize, beans and feed crops
- Area to irrigate	ha
Data for validation	
- Reservoir volumes	m^3
- Remotely sensed data with an adequate resolution and acquired at a date appropriate for land use classification	ha of irrigated land

$$\frac{\Delta S_{\text{Ri}}}{\Delta t} = \sum_{x=1}^{n} Q_{\text{u},x} + \sum_{y=1}^{m} R_y - Q_{\text{d}} - W \tag{2}$$

where ΔS_{Ri} is the change in storage in the river branch over a time interval Δt, including the underlying alluvial aquifer, $Q_{\text{u},x}$ is discharge coming in from a directly upstream river branch x, R_y is runoff from riparian grid cell y, which is located in the local sub-catchment, Q_{d} is the discharge flowing into the downstream river branch and towards the next downstream node, and W is water withdrawal by water users on downstream riparian lands. It is assumed that farmers try to fulfil irrigation water demands. A part of irrigation withdrawals is returned to the river through return flows that are included in R_{SS} of o-grid cell.

The water balance of a reservoir can be expressed as follows (all units in m^3/s):

$$\frac{\Delta S_{\text{Re}}}{\Delta t} = \sum_{x=1}^{n} Q_{\text{u},x} + \sum_{y=1}^{m} R_y + P - E - Q_{\text{d}} - W \tag{3}$$

where ΔS_{Re} is change in storage of the storage reservoir over a time interval Δt; $Q_{\text{u},x}$ is discharge coming in from a directly upstream river branch x; R_y is runoff from riparian grid cell y, which is located in the local sub-catchment; P is rainfall on the reservoir surface area which is updated according to a volume–surface relationship for the reservoir; E is evaporation from the reservoir surface area; the released outflow of a reservoir that is controlled by operating an outlet and consists of discharge (Q_{d}) and downstream withdrawal (W).

2.3. Agent decision-making and water use

Farmers in semi-arid regions depend on an environment that in the ABSTRACT model is characterised by only a few factors. Besides rainfall, accessibility of sources for irrigation and flooding of agricultural fields are taken into account. Both flood risk and access to water resources are related to local topography. The difference between the height of a plot and the varying water level of a local water source influences practical availability of water and thus land use decisions. Crop choice and the extent of the irrigated land are both influenced by indicators of water availability. The influence of these indicators is manipulated by using randomly generated probability generators that represent preferences of water users in a certain community. A farmer's geographical location within the basin influences his vulnerability to water use by other farmers. Three different locations for access to sources of irrigation are distinguished: upstream of a reservoir, on a reservoir floodplain and downstream of a reservoir. The principal source of water for irrigation of farmers located upstream of a reservoir is the river or the alluvial aquifer from which water is directly pumped. In the floodplain of a reservoir water is pumped from groundwater connecting to the nearby reservoir. Downstream of a reservoir farmers generally depend on water released from the reservoir. Fig. 3 shows a flowchart of farmer decision-making on land use for those of their plots that are equipped for irrigation. Its implementation for the Jaguaribe basin is described in Section 3.

Although the decision-making process by an allocation committee deciding on reservoir operation is a complex decision-making process involving various actors, autonomous decision-making by Allocation Committee-agents is not implemented in this study. Since the focus of this study is on the behaviour of individual water users rather than on group-decision-making regarding reservoir releases, an empirical data-set on reservoir releases has been used.

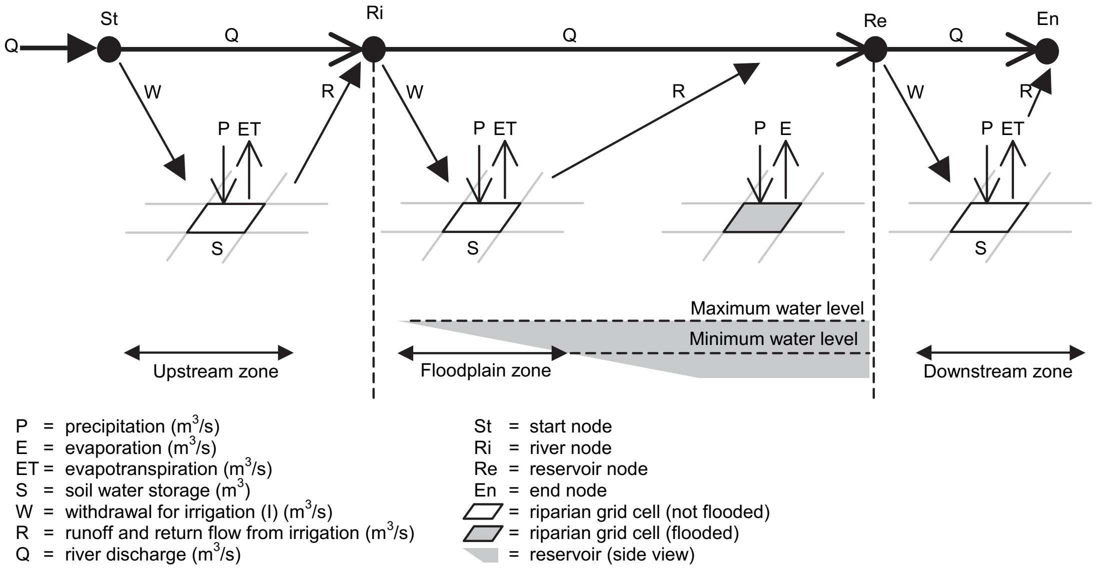

Fig. 2. Schematisation of the link between the field water balance in the riparian lands and the river network and its water balance.

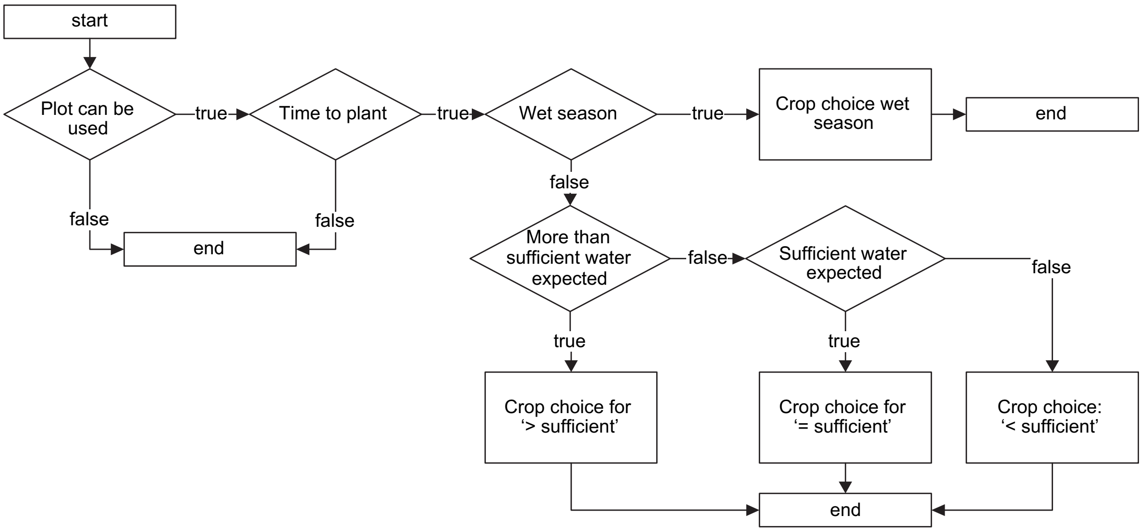

Fig. 3. Study area, with indication of nodes and irrigation areas.

2.4. *Data use*

For an adequate representation of the environment and water users in the ABSTRACT model the following data are required: data on meteorological parameters, soil and crop characteristics relevant to water balance calculations, data on the water system and survey data on decision rules of farmer–agents. For validation of the ABSTRACT model data on reservoir volumes and land use are used (Table 1).

3. Model application for the Jaguaribe basin

3.1. *Study area and spatial representation*

In many parts of the semi-arid Northeast of Brazil, water use is dominated by irrigation. The amount of water needed for a particular land use differs over space and time, depending on climatic and geophysical conditions. The Jaguaribe basin is located within the institutional borders of the state of Ceará and covers approximately 74,000 km^2 (Fig. 4).

Annual precipitation ranges from 450 to 1150 mm on average, with high levels of temporal and spatial variability (FUNCEME, 2008). Most rain falls in the period from 1 January to 30 June. Temporal rainfall variability is highly significant on a range of levels: decadal variability (Souza Filho and Porto, 2003), inter-annual variability, seasonal variability and variability on the time scale of a week (Enfield et al., 1999; Gaiser et al., 2003; Smith and Sardeshmukh, 2000; Uvo et al., 1998). Our study area is located around the Orós reservoir. Two other public reservoirs in the area are the Trussu reservoir and the Lima Campos reservoir. A tunnel connects the Orós reservoir and the Lima Campos reservoir providing the latter with additional inflow.

Water allocation management and water use for irrigation are discussed intensely in Ceará, because of persistent pressure on water reserves in strategic reservoirs (COGERH, 2001, 2003; Döll and Krol, 2002; Johnsson and Kemper, 2005; Lemos and De Oliveira, 2004).

Conflict among water users in the Jaguaribe basin is strongly influenced by the geographical locations at which they use the resource. User communities located upstream of reservoir dams tend to disagree with downstream user communities with respect to water releases (Broad et al., 2007; Taddei, 2005). Upstream users generally tend to oppose water releases while downstream users tend to favour them. From analysis of remotely sensed imagery and government data on agricultural yield and production we learned that there is strong spatial and temporal heterogeneity of agricultural activity in the area under study (Leskens, 2006; Van Oel et al., 2008).

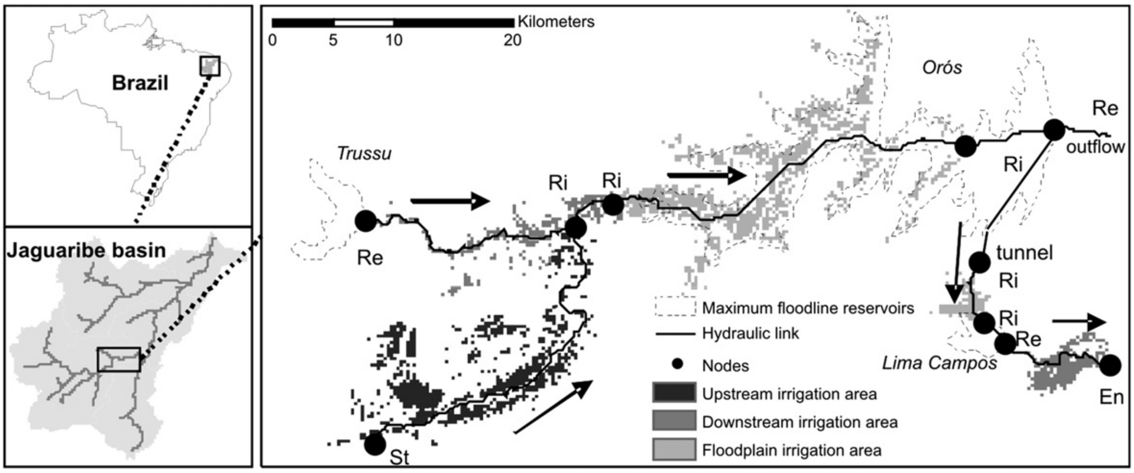

Fig. 4. Geographical locations of farmers in the survey of 2006 (Taddei et al., 2008).

Farmers in the area generally cultivate riparian plots with an area of between 5 and 10 ha (COGERH, 2001). The grid cell size of our model is 7.29 ha, corresponding to nine grid cells of the digital elevation model (DEM) that is used (EMBRAPA, 2006). The DEM has a grid cell size of 90×90 m^2 and a vertical resolution of 1 m. For the elevation of the cells in the ABSTRACT model the value of the middle cell of squares composed of 9 DEM grid cells is taken.

For the whole study area it is supposed that evaporation losses are 25% of the withdrawal. This is a rough estimate. Farmers in the area use irrigation methods varying from flooding paddies, using furrows to applying drip techniques. It is assumed no major changes with regard to land management have occurred during the period 1996–2005. Irrigation canals also vary in efficiency. No reliable data on actual efficiency is available.

3.2. *Farmer–agent decision-making*

Rules for farmer decision-making with respect to the area of land to be irrigated and the type of crop to grow are based on a survey involving water users from all over the Jaguaribe valley (Taddei et al., 2008). During the period May–August 2006, interviews with 602 irrigation farmers in 149 localities (in 14 municipalities) in the Jaguaribe valley were conducted. A random sampling method was used. Data from 55 farmers located in the study area (Fig. 5) have been used for this study. For the survey farmers were interviewed on their decisions regarding land use in both the wet and the dry seasons. Three qualitatively different situations were outlined to the respondents for the dry season: water availability that is regarded as less-than-sufficient, as sufficient or as more-than-sufficient. The ways survey respondents from different zones in the study area operate in these three situations in respect of crop choice and area of land to irrigate are presented in Table 2.

Based on survey data and interviews with local experts in 2005 and 2006, three key elements of farmer decision-making regarding crop choice and the area of land to irrigate are identified. The first is rainfall expectation, especially important for those who rely on short-term storage reservoirs and alluvial aquifers. The second key element is the quantity of stored water resources in the primary water source of the water user. The third element is flood risk, which is important to those farmers who utilise the fertile lands on the floodplains of large reservoirs. Other factors, such as individual financial resources and crop markets are not taken into account in this study. Rules for farmer decision-making that take into account flood risk and limitations on the pumping capacity for individual water users involve a comparison between the altitude of the grid cell that a farmer–agent occupies and the water level in the reservoir or aquifer that is relevant to the specific location (Table 3). A comparison between observed water availability in the study area and survey outcomes suggests that farmers from different locations disagree on the circumstances that lead to 'less-than-sufficient', 'sufficient' and 'more-than-sufficient' water availability. Also, upstream farmers generally favour sufficient water availability over more-than-sufficient and less-than-sufficient, while downstream farmers don't mind more-than-sufficient water availability (full reservoirs).

In the ABSTRACT model three groups of farmers are differentiated according to their relative geographical location: upstream farmers, floodplain farmers (corresponding to farmer groups B and C), and downstream farmers (corresponding to farmer group A). Implementation of the rules from Fig. 3 for the three different farmer groups in the study area is described in Table 3 while Table 4 gives the values of rainfall that are used as thresholds on which upstream and floodplain farmers decide whether they locally expect sufficient water availability during the dry season. This deterministically shapes the extent of the cropping area in a zone. Crop choice by individual farmer–agents is simulated randomly, using the distribution derived from empirical data on of crop choices presented in Table 2. Because representative survey respondent records were not available for all parts of the study area (Fig. 5), data from respondents from farmer group A are used for farmers located downstream of both the Trussu and the Lima Campos reservoirs. For upstream farmers data for farmer group B have been used.

For the simulated period of 1996–2005 a time series of reservoir release quantities (COGERH, 2006) is used.

3.3. *Input data*

For rainfall variability use is made of meteorological data from the meteorological research institute of Ceará (FUNCEME, 2006). Data on potential evapotranspiration are obtained from ClimWat (FAO, 2006). Data for the measurement station at Iguatu, centrally located in the study area, are used. Soil characteristics are obtained from the database that was developed for the WAVES project (Gaiser et al., 2003). Discharges of upstream inflow are derived from the national Hidro database (ANA, 2006). Reservoir volumes, releases and volume–surface relationships for the reservoirs Trussu, Lima Campos and Orós are obtained from the water management authority in Ceará (COGERH, 2006). The altitude of individual grid cells in the model is determined using a 90 m resolution digital elevation model from the Brazilian Agricultural Research Corporation (EMBRAPA, 2006). Runoff coefficients for

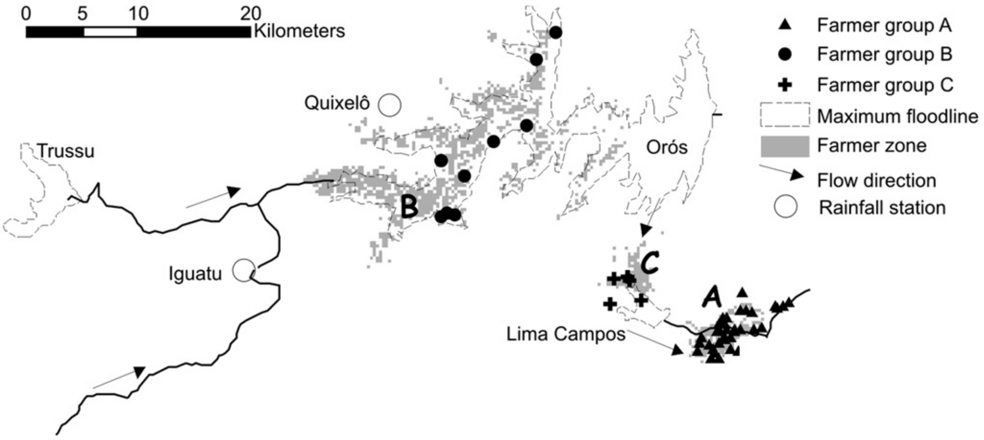

Fig. 5. Land use decision flowchart.

Table 2
Summary of survey results: land use variation by farmers under different water availability circumstances (Taddei et al., 2008).

		Fraction of the area used for irrigated agriculture	Crop area as a fraction of irrigated area			
			Rice	*Maize*	*Beans*	*Feed crops and other*
Farmers zone A	*Dry season*					
	Local water availability < sufficient	0.60	50%	1%	15%	34%
	Local water availability = sufficient	1.00	60%	1%	14%	26%
	Local water availability > sufficient	0.97	66%	1%	14%	19%
	Wet season (2006)	0.54	41%	21%	6%	32%
Farmers zone B	*Dry season*					
	Local water availability < sufficient	0.79	63%	24%	10%	3%
	Local water availability = sufficient	1.00	67%	17%	8%	8%
	Local water availability > sufficient	0.83	67%	10%	12%	11%
	Wet season (2006)	0.42	0%	64%	30%	6%
Farmers zone C	*Dry season*					
	Local water availability < sufficient	0.60	52%	0%	29%	20%
	Local water availability = sufficient	0.74	56%	0%	23%	21%
	Local water availability > sufficient	0.71	59%	0%	20%	22%
	Wet season (2006)	1.00	20%	58%	10%	11%

runoff into the Trussu, Lima Campos and Orós were obtained from a hydrologic study for Ceará which includes the study area of this study (Güntner, 2002). For initial land cover/use, data are used from: annual agricultural production data of IBGE for the period 1990–2005 (IBGE, 2006), seasonal agricultural production data for the period 2003–2005 of the Iguatu office of the agricultural institute for the state of Ceará, EMATERCE, and land use classifications using remotely sensed data for the dry season. The following images were used: Landsat TM, (path–row) 217–64 (25 October 2000, 13 November 2001, 31 October 2002); CB2CCD (path–row) 150–107 (22 November 2003, 29 September 2004, 24 October 2005); and CB2CCD (path–row) 151–107 (19 November 2003, 26 September 2004, 21 October 2005). Classification of the remotely sensed data gives a good estimate of the extent of the area that has been irrigated in the period 2000–2005, since they are obtained during the dry seasons in that period. Locations that have been identified as irrigated for at least one of the images are considered to be equipped for irrigation during the simulated period of this study. In Section 4.2 land use classification results of the remotely sensed data are also used to validate simulation outcomes based on survey data. Survey data are obtained from a survey conducted in 2006 among water users in the Jaguaribe valley (Taddei et al., 2008).

3.4. Method of validation

To test the performance of the ABSTRACT model, reservoir storage and land use are considered. An empirical data-set of reservoir volumes for the Orós reservoir (COGERH, 2006) is compared to the outcomes of our simulations. This is done by determining the Nash–Sutcliffe efficiency coefficient (Nash and Sutcliffe, 1970) for seasonal volume changes of the reservoir. Nash–Sutcliffe efficiencies can range from $-\infty$ to 1. If model efficiency is 1, the model is perfectly accurate. The measure is also known as coefficient of determination and R^2. Volume changes in the wet season (1 January–30 June) are mainly caused by rainfall, while volume changes in the dry season (1 July–31 December) are mainly caused by water use. Simulations of the ABSTRACT model are compared to model runs where no water is abstracted at all and to model runs where land use is coupled with the average water use over the 10 years.

Table 3
Rule implementation for different farmer types.

Rule	Upstream farmer	Floodplain farmer	Downstream farmer
Plot can be used if:	There is not already a crop on the plot	There is not already a crop on the plot & For dry season: The plot is not too high (< 7 m above water level) & the plot is not flooded For wet season: The plot is high enough (> 4 m above water level)	There is not already a crop on the plot
Time to plant if:	Rainfall >20 mm in 10 days & date between 1 January and 10 April or: Date between 1 July and 1 September & at least 30 days after harvesting the wet season crop	Rainfall >20 mm in 10 days & date between 1 January and 10 April or: Date between 1 July and 1 September & at least 30 days after harvesting the wet season crop	Date between 1 January and 10 April or: Date between 1 August and 31 December
Wet season if:	1 January–30 June	1 January–30 June	1 January–30 June
Farmer expects more-than-sufficient water for the dry season if:	Rainfall during the wet season > higher threshold	Rainfall during the wet season > higher threshold	Reservoir volume at 1 July > 70% of capacity
Farmer expects sufficient water for the dry season if:	Rainfall during the wet season > lower threshold	Rainfall during the wet season > lower threshold	Reservoir volume at 1 July > 35% of capacity

Table 4
Rainfall (mm) during the wet season (1 January–30 June) at two locations.

	Quixelô[a] (1988–2005)	Iguatu[a] (1974–2005)
Average 1 Jan–30 Jun	661	863
Lower 25% (lower threshold)	<534	<642
Normal 50%	534–789	642–1005
Higher 25% (higher threshold)	>789	>1005

[a] Locations of rainfall stations are shown in Fig. 4.

Apart from model validation in respect of the water balance of the Orós reservoir, the farmer decision-making rules that are based on survey data are separately validated. To find out whether the ABSTRACT model is successful in resembling inter-annual water use variation, model outcomes should preferably be compared to empirical data of water use. Actual water use is however poorly monitored in the study area. Since water use for irrigation strongly relates to agricultural land use, especially during dry periods, land use data can be used for validation as well. These data are also scarce, but for the period 2000–2005 remotely sensed imagery of the area is available. The images that are described in the previous section have been used for land use classifications in a study by Leskens (2006). The extent of irrigated area as classified by Leskens is compared to the outcomes of the simulations of this study. This is done separately for the zones of farmer groups A, B and C (Fig. 5).

4. Simulation results and validation

4.1. Reservoir water balance

Reservoir volumes in the main reservoir in the study area, the Orós reservoir, can be predicted with reasonable accuracy by the ABSTRACT model (Fig. 6). For seasonal volume changes the Nash–Sutcliffe efficiency coefficient (Nash and Sutcliffe, 1970) is 0.95 (Fig. 7). For the dry season (1 January–30 June) alone the result is 0.98. This can be explained by the fact that uncertainties over rainfall are less dominant during the dry season. Since farmer decision-making on crop choice involves randomly generated probabilistic procedures, three runs were done. The results presented in Figs. 6 and 7 are all based on the average of these three runs. For each of three different conditions (‘simulated’, ‘no irrigation’ and ‘no variations irrigation’) all three runs resulted in a similar outcome for the Nash–Sutcliffe efficiency coefficient.

Fig. 6 clearly shows that including water use significantly improves model outcomes with respect to reservoir volumes: Simulations b and d much better resemble a than c does. This confirms that water use for irrigation influences water availability dramatically. To analyse the effects of feedback processes between water use and water availability, the inclusion of variations in irrigation is also evaluated. Introducing variations in water use for irrigation that are based on survey data regarding intended land use did not significantly influence simulation outcomes. In other words, including a feedback from water storage to water use variability does not result in significant improvements in simulated reservoir volumes for this study area. Fig. 6 clearly shows differences between actual volume changes and simulated volume changes, notably in the years 2000 and 2002. In 2000 the wet season volume increase is underestimated, while it is overestimated in 2002. In wet seasons rainfall and runoff can cause sudden changes in volume.

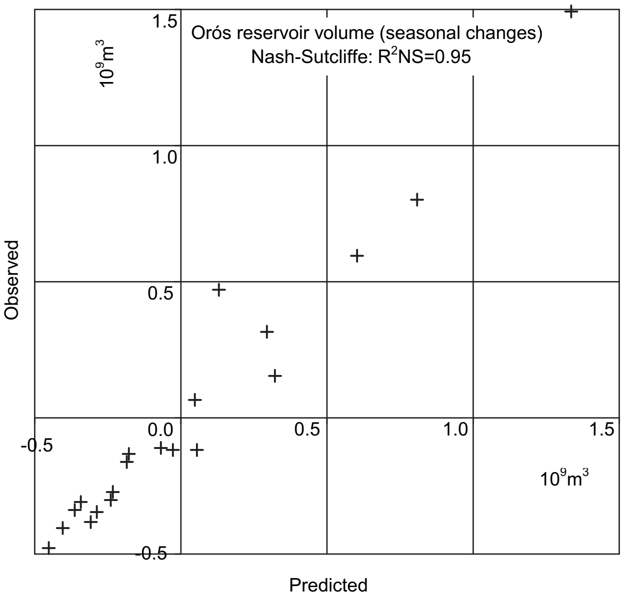

Fig. 7. Observations and predictions of seasonal volume changes over the period 1996–2005 for the Orós reservoir. Each year has two seasons: the wet season starts on 1 January and ends on 30 June and the dry season starts on 1 July and ends on 31 December.

4.2. Irrigated area and water use

Simulation outcomes of water use for the zones of farmer groups A, B and C are presented in Fig. 8. This figure clearly shows

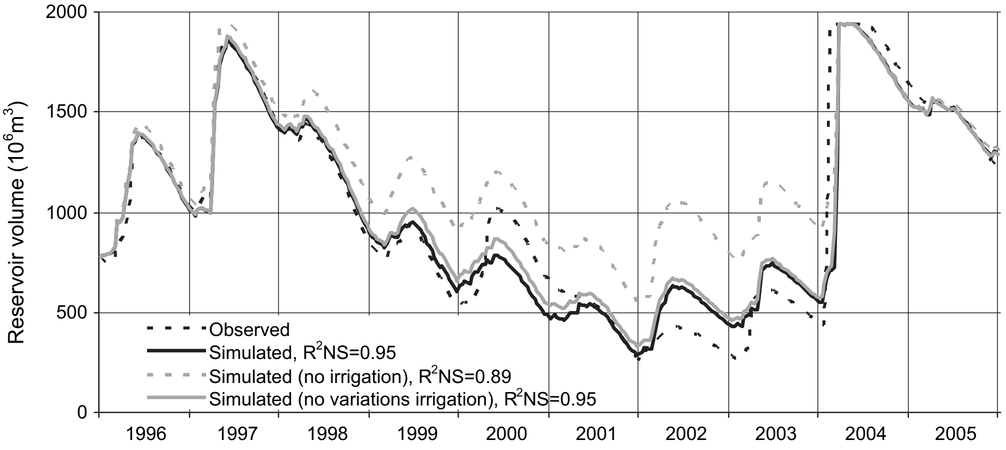

Fig. 6. Observed and simulated reservoir volumes for the Orós reservoir.

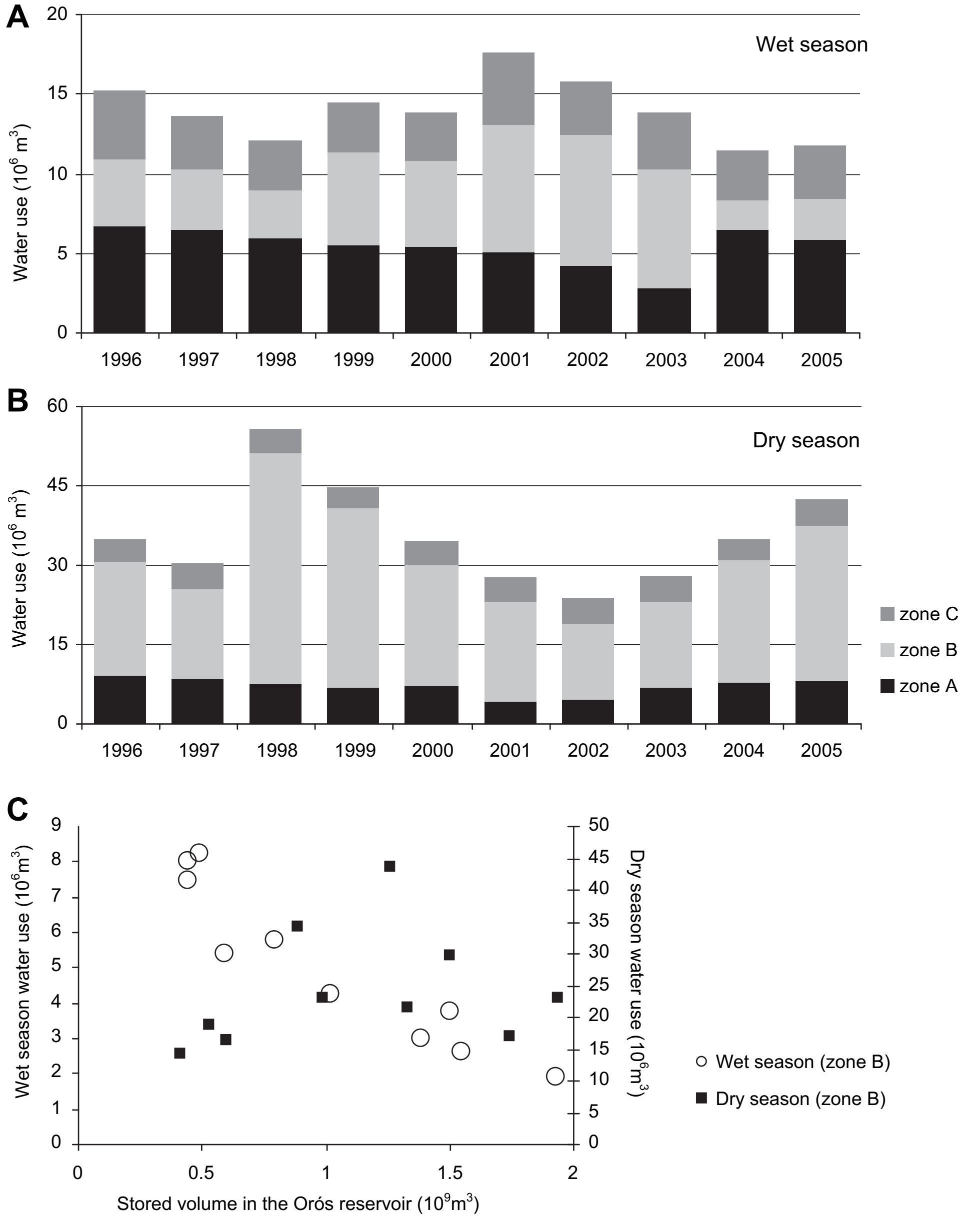

Fig. 8. Simulated water use in the zones of farmer groups A, B and C during the wet and the dry seasons for the period 1996–2005. In the lower graph storage levels in the Orós reservoir for the wet season (10 April) and the dry season (1 July) are plotted against water use in the zone of farmer group B.

that the ABSTRACT model enables us to analyse variations in water use over time at different locations in the study area. Interestingly, the results presented in Fig. 8, when compared to Fig. 6, suggest that for the wet season high (low) water availability results in low (high) water use; however high (low) water availability results in high (low) water use during the dry season. Especially high water use in the wet season if there are relatively low storage levels in reservoirs increases water stress during the following dry season. As can be seen in Fig. 8, the largest water use variations are seen in zone B. The high water use in the dry seasons of 1998 and 2005 can be explained by the relatively high water storage in the Orós reservoir in these years (Fig. 6). The high water use in the wet season of 2001 is the result of the fact that water storage in the Orós reservoir is comparatively low (Fig. 6) so that there is quite a lot of fertile land available for irrigated agriculture. The relatively high water use in the wet season of 2001 resulted in a further depletion of available water resources, which reduced possible water use in the dry season of 2001, especially for zone A at the downstream end of the study area.

To test the validity of the specific representation of feedback processes between water use and water availability in our modelling approach, the simulated variations for water use should be compared to observations. As data on water use are not available for the study area, it was decided to compare simulated land use patterns with land use classifications from remotely sensed images. Simulation outcomes for irrigated area for the zones of farmer groups A, B and C, were compared to a data series of land use classifications, one for each dry season in the period 2000–2005. In the simulation runs that were done specifically for this analysis, farmer-agent decision-making takes into account observed reservoir water levels (COGERH, 2006) rather than simulated water levels. This was done to isolate the simulated decision-making procedures from uncertainties related to input data for rainfall and runoff, which could result in water levels that conflict with observed water levels seen in Fig. 6. Since farmer decision-making regarding crop choice involves randomly generated probabilistic procedures, multiple runs were done. This was done to explore the sensitivity of model outcomes to variations due to these procedures. The results of three runs (Fig. 9) show small differences, which suggest low sensitivity to the procedures. A more extensive uncertainty assessment was not performed.

For a part of the study area model outcomes resemble variations in irrigated area that have been observed in the land use classifications quite well. The results for the zones of farmer groups A, B and C are shown in Fig. 9.

For the zone of farmer group A simulation outcomes show a reasonable resemblance to land use classifications. All farmers in zone A use plots within an irrigation scheme that is located downstream of a single water source: the Lima Campos reservoir. For farmers in this zone, modelled as downstream farmers, the water availability situation is directly related to the water availability in the Lima Campos reservoir that supplies the canal network of their irrigation scheme with water. Therefore heuristics of decision-making are likely to be homogenous for all members of this group.

The decision-making heuristics for farmer group B are likely to be quite homogenous as well. The farmers depend on one clearly defined resource: the Orós reservoir. All farmers in this zone are modelled as floodplain farmers. Uncertainty over the representativeness of individual survey respondents in zone B might be of interest here, because the altitude at which farming activities take place influences water availability and flood risk. Although geographical locations of residence are known for all respondents, the location of the land they use for agricultural purposes is unclear. Therefore it is not possible to link the heuristics of individual survey respondents to exact locations within the zone.

For the zone of farmer group C the ABSTRACT model does not perform well. As with farmer group B, the exact geographical location of agricultural activities of respondents from this zone is not clear. In addition, farmers in this zone depend on different water sources for irrigation. Water from the upstream Orós reservoir is available to only some of the farmers, because of a tunnel between the Orós and the Lima Campos reservoirs. Other farmers do not have access to that water, but can pump water out of the Lima Campos reservoir and may be susceptible to flooding. We have chosen to represent all individuals in this zone in the same way, treating them as downstream farmers dependent on the volume in the upstream Orós reservoir. The fact that flooding limits land availability near the Lima Campos reservoir is taken into account as well.

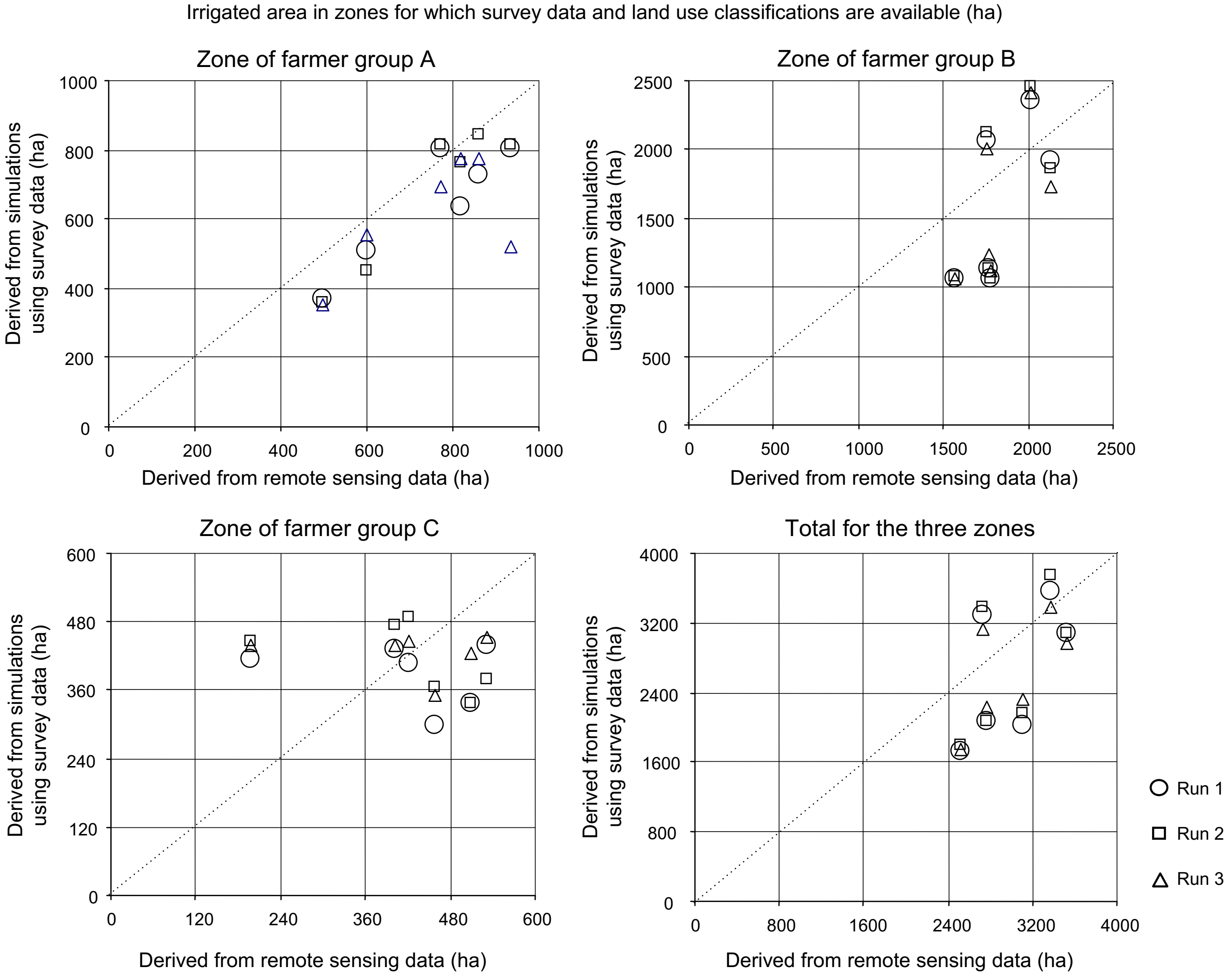

Fig. 9. Comparison between outcomes for irrigated area as a result of our simulation (based on survey data) and land use classification for remotely sensed imagery. Irrigated area is shown for the three specific zones for which data were available and for the total study area.

5. Conclusion and discussion

Applying an MAS approach is useful in representing feedback mechanisms between water availability and water use in the semi-arid Jaguaribe basin. It has been shown that it is possible to validly depict spatial–temporal variability of water availability influenced by water use and vice versa. The ABSTRACT model outcomes resemble observed variability of water availability in the study area for the period 1996–2005.

Direct validation of the model outcomes with respect to water use was not possible due to a lack of available data on water use. However, land use classifications from remotely sensed data offered good opportunities to validate the simulation of land use, which is the main determinant for water use in the ABSTRACT model. Decision-making heuristics regarding crop choice and the amount of land to irrigate were implemented by equipping farmer–agents with rules based on survey data. Simulation outcomes roughly resemble land use classifications from remotely sensed data for the study area. Resemblance is closest for farmer groups dependent on clearly identifiable water sources. Representing heterogeneity of farmer decision-making based on the available survey data was not possible on a local scale, as the exact geographical location of agricultural activities was unknown.

In modelling human–environment interactions it is important to distinguish between positive and negative system feedbacks (Verburg, 2006). Interestingly, we have encountered and represented both positive and negative correlations between water availability and water use. Wet season water use is negatively influenced by changes in water availability, whereas dry season water use is positively influenced by this. This means that wet season use potentially amplifies water stress during the following dry season. The character of the dynamics is determined by a combination of the agents' heuristics (especially for dry season dynamics) and the spatial distribution of agents. Representing these dynamics, including the influence of rainfall and water storage variations on water use for irrigation, as done here in a MAS, is essential for obtaining a more complete understanding of system dynamics in semi-arid river basins. Thus it is potentially valuable in assessing the impact of future investments in infrastructure on water availability distribution over space and time. Multi-agent simulation is especially suited to representing these dynamics.

The outcomes of this study confirm that, in the Jaguaribe basin, water availability is a major factor in farmer decision-making on land use and the related water use for irrigation. However, farmer decision-making is known to be influenced by many factors other than the ones taken into account in the ABSTRACT model. One of these other factors is a constantly changing environment, in which the market prices of different crops and the use of technologies for irrigation can change for a variety of reasons. It is likely that developments outside the study area, such as global economic developments and national policies, also influence farmer decisions with respect to water use for irrigation. A further factor is the availability of information to farmers. In some years, for example, meteorological predictions might be more reliable than in others. The availability of information can vary and change significantly over time and among farmers in the study area. Meteorological forecasts and knowledge of agricultural practices may be available to some farmers, while not reaching others. In addition, it is possible that farming strategies change over the years due to structural changes in the environmental conditions experienced by farmers.

The results of this study suggest that an MAS approach like the ABSTRACT model can be useful in exploring the impact of technological developments and policies. Examples include the implementation of infrastructural projects, reservoir operation strategies and policies stimulating innovations regarding water saving.

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