Physics and Chemistry of the Earth 47–48 (2012) 173–181

Contents lists available at SciVerse ScienceDirect

Physics and Chemistry of the Earth

journal homepage: www.elsevier.com/locate/pce

Application of multi-agent simulation to evaluate the influence of reservoir operation strategies on the distribution of water availability in the semi-arid Jaguaribe basin, Brazil

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ARTICLE INFO

Article history:
Available online 6 August 2011

Keywords:
Jaguaribe basin
Semi-arid
Water availability
Water use
Multi-agent simulation
Brazil

ABSTRACT

Studying the processes responsible for the distribution of water resources in a river basin over space and time is of great importance for spatial planning. In this study a multi-agent simulation approach is applied for exploring the influence of alternative reservoir operation strategies on water use distribution in the semi-arid Jaguaribe basin in case of decreasing rainfall. Water use distribution is analyzed both for one specific subbasin – our study area – and for the river basin level. Agents in this study are farmers that adapt to local variations in water availability. In this way both natural and human influences on water availability are taken into account. This study shows that a decrease in rainfall and runoff in the Jaguaribe basin leads to a transition of water use from the dry season to the wet season. The dry season water use decreases because of reduced water availability in the dry season. This mainly is the result of reduced rainfall and runoff in the wet season and the consequent increased water use for irrigation in the wet season. A decrease in rainfall and runoff also leads to a relative transition of water use from downstream to upstream at the basin scale. Strategic reservoir operation enables local water managers to offset the effect of decreasing rainfall and runoff with regards to water use at the subbasin level, at the cost of further decreasing water availability at the basin level.

1. Introduction

Long term trends in freshwater availability for human use emerge through an interplay of physical changes in the environment (e.g. climate change) and changes in activity levels of water using functions. Often climate change impact assessments analyze the availability of freshwater without taking into account water user responses to variations and changes in water availability (Gaiser et al., 2003; Kundzewicz et al., 2008; Alcamo et al., 2003). Kundzewicz et al. (2008) argue that the impact of changes in rainfall and runoff on water use depends partly on population characteristics and the way that water managers adapt to changing circumstances. In this study we are interested in the effect of alternative water management strategies (reservoir operation), while taking into account that water user responses to changes in water availability can amplify and attenuate water stress in case of decreasing rainfall and runoff.

For this study the following factors are of particular importance: rainfall, reservoir operation, water availability, water use, and more in particular the feedback relation between water availability and water use under influence of rainfall variability and reservoir operation. For the spatially-explicit inclusion of feedback mechanisms between water use and water availability use is made of multi-agent simulation (or multi-agent systems). Multi-agent simulation (MAS) models that are used for studying and informing natural resource management consist of a spatial model generally representing geophysical aspects of a natural resource system and an agent-based model representing human decision making that is related to or relevant for the system. It is increasingly acknowledged that MAS is an adequate technique to represent human-environment interactions (e.g. Bousquet and Le Page, 2004; Filatova et al., 2009; Matthews et al., 2007; Parker et al., 2002, 2003; Verburg, 2006). MAS models may help to portray systems in which interdependencies between agents and their environment are essential for a proper understanding of processes where the heterogeneity of agents or their environment critically impacts model outcomes and where adaptive behavior at the individual or system level are relevant for the system under study (Parker et al., 2003). With regard to policy analysis for water resource management, Berger et al. (2007) and Schlüter and Pahl-Wostl (2007) show that MAS is helpful for a better understanding of the complexity of water use and water users within sub-basins.

In previous studies for the semi-arid Jaguaribe basin in the Northeast of Brazil the effects of water use for irrigation on water availability distribution were explored (van Oel et al., 2009, 2008)

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doi:10.1016/j.pce.2011.07.051

and have been depicted in the ABSTRACT (Agent-Based Simulation Tool for Resource Abstraction in a CatchmenT) model. The model was satisfactory validated for recent developments using empirical data on land use and water availability (van Oel et al., 2010). In the ABSTRACT model agents employ decision-making heuristics. In the present study the ABSTRACT model is used for studying the effects of alternative reservoir operation strategies in case of decreasing rainfall quantities. For clarity, the reservoir operation strategies have been kept as simple as possible.

2. Study area

In many parts of the semi-arid Northeast of Brazil, water use is dominated by abstractions for irrigation. The Jaguaribe basin is located within the institutional borders of the state of Ceará and covers approximately 74,000 km^2 (Fig. 1). The study area comprises a midstream sub-basin, covering 2400 km^2. Water allocation management and water abstractions for irrigation are intensely discussed in Ceará because of persistent pressure on water reserves in strategic reservoirs (Johnsson and Kemper, 2005; COGERH, 2001, 2003; Döll and Krol, 2002; Lemos and De Oliveira, 2004; Krol et al., 2011). Current annual precipitation ranges from 450 to 1150 in average, with high levels of temporal and spatial variability (FUNCEME, 2008). Most rain falls in the period January–June. Temporal rainfall variability is highly significant on a suite of scales: decadal variability (Souza Filho and Porto, 2003), inter-annual variability, seasonal variability and variability at the time scale of a week (Uvo et al., 1998; Gaiser et al., 2003; Smith and Sardeshmukh, 2000; Enfield et al., 1999). A global scale study on future water availability projects a potential decrease in groundwater recharge of 70% by the 2050s for the Northeast of Brazil in comparison to recent values (Döll and Flörke, 2005). Our study area (Fig. 1, right panel) is located around the Orós reservoir (storage capacity: 1.94×10^9 m^3). Two other public reservoirs in the area are the Trussu reservoir (storage capacity: 0.30×10^9 m^3) and the Lima Campos reservoir (storage capacity: 0.07×10^9 m^3). A tunnel connects the Orós reservoir and the Lima Campos reservoir providing the latter with additional inflow (maximum flow: 3 m^3/s).

Farmers in the study area generally cultivate on riparian plots with an area of between 5 and 10 ha (COGERH, 2001). Conflict among water users in the Jaguaribe basin is strongly influenced by the geographical locations at which they use water. User communities located upstream of reservoir dams tend to disagree with downstream user communities with respect to water releases (Taddei, 2005; Broad et al., 2007). In times of water stress upstream users generally tend to oppose water releases while downstream users tend to favor 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).

3. Methods

The research adopts a simulation modeling approach; the model used, together with its input data, is described below, in accordance with the ODD protocol for describing agent-based models, as proposed by Grimm et al. (2006). The water balance module is expanded on, being of major importance to the present study. Model applications are described in the scenario-section.

3.1. Model description

The ABSTRACT model is designed to simulate the interplay of water availability and water use in basins and sub-basins that deal with water scarcity by storing water in surface water storage reservoirs in order to facilitate irrigation through multi-annual periods of drought. The ABSTRACT model is developed in CORMAS, a platform running on a VISUALWORKS environment (Bousquet et al., 1998). The model represents feedback processes between water availability and water use for irrigation. Topography, hydrological processes, possibilities of freshwater storage and water use

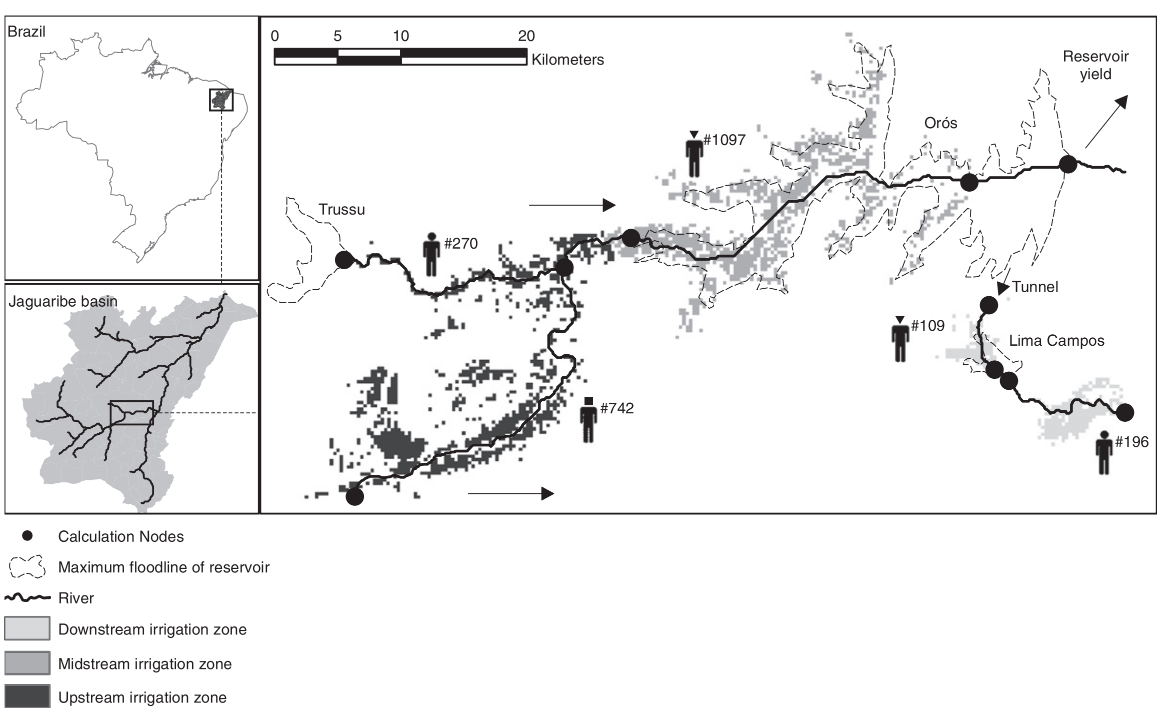

Fig. 1. Study area: the different irrigation zones are labelled upstream-, midstream-, and downstream irrigation zone. For each riparian zone the amount of agents is indicated.

for irrigation characterize the spatially-explicit cellular model environment. The following model description is made in accordance with the ODD protocol as proposed by Grimm et al. (2006).

3.1.1. Purpose of the model

The main purpose of the model is to include the feedback-mechanisms between water availability and water use in exploring the evolution of water availability distribution in space and time. Water availability can be very different from one place to the other within one basin. Water use depends on human actions and the actual availability at the location of intended use.

3.1.2. State variables and scales

The spatial extent of the model is a river (sub)basin, covering around 2400 km^2. The temporal scale extends to 50 years. Water availability is represented in local resources such as surface water storage reservoirs and river branches including alluvial aquifers. Water users operate at the local level corresponding to a grid size of 270 × 270 m (7.29 ha) corresponding to 9 cells of a digital elevation model (EMBRAPA, 2006). The model uses a 10 day time-step.

In the ABSTRACT model farmer agents make land use decisions that are based on actual and expected water availability in the local sources that are used for irrigation. Farmer agents occupy a single cell in a cellular river basin landscape. The preferences of farmers at different locations for situations with water availability that is considered less than sufficient, sufficient or more than sufficient are obtained from an empirical survey data set (Taddei et al., 2008). In the environment those agents that depend on the same local water resource (e.g. a river/alluvial aquifer or reservoir) are assigned the same preferences. Each of these agent groups is categorized into one of the following types: river users, floodplain users or reservoir users (Fig. 2). River users are not in the vicinity of surface water storage reservoirs and do not receive water from upstream reservoirs. Floodplain users are upstream of a dam but can still obtain water from the reservoir. They also face danger of flooding. Reservoir users can obtain water that is released from a reservoir.

The state variables at their specific locations (grid cells) may vary. An overview of model parameters and their units is presented in Table 1. In the model application for the area around the Orós reservoir five different zones with specific agent types are defined (Fig. 1).

3.1.3. Process overview and scheduling

Agents represent farmers that are situated at specific geographical locations and make land-use decisions, followed by actions, affecting water availability in the environment. The modeling sequence is the following: (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 updated. This is done at the beginning of every 10-day time step. Biophysical processes include crop growth, water balance calculations of agricultural fields, alluvial aquifers and surface water reservoirs. Decisions on land use are made by individual agents, taking into account local conditions (see Fig. 3 and Table 2).

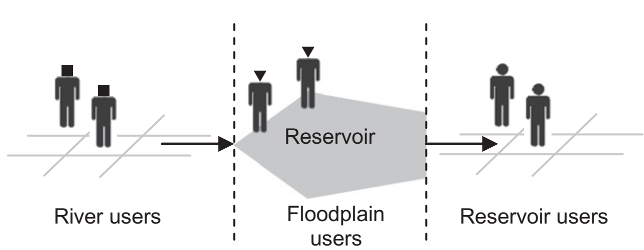

Fig. 2. The three different types of agents and relative their position to a reservoir: river users, floodplain users and reservoir users.

Table 1
Parameters and data requirement of the ABSTRACT model (van Oel et al., 2010).

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	mm/m
– Water available for evaporation	mm
– Water readily available for evaporation	mm
Crop characteristics (Doornbos and Pruit, 1977)	
– Four vegetative period durations (Lini, Ldev, Lmid, Lend)	days
– Three crop coefficients (KCini, KCmid, KCend)	–
– Initial root depth	mm
– Final root depth	mm
Water system data	
– Discharges of upstream inflow (only if the area is not an isolated catchment)	m3/s
– Reservoir releases and surface–volume relationships	m2/m3
– 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	m3
– 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

3.1.4. Design concepts

Water availability in the modeled area changes as water is used and hydrological processes take place. Agent behavior influences water availability and in this way influences water use by agents at later dates. Both the agent itself and agents located relatively downstream may adapt to the resulting changes in water availability. In this way water scarcity patterns and the occurrence of basin closure (Seckler, 1996) emerge as a collective result of the behavior by individual agents. Agents strive for cultivation of their preferred crops. Crop choice and the extent of the irrigated land are influenced by water availability. The actual land use is further manipulated by using randomly generated probability generators that represent preferences of water users in specific parts of the study area. These preferences are those identified from Taddei et al. (2008). Agents predict whether water availability will be less-than-sufficient, sufficient ore more-than-sufficient. Their prediction is based on water availability at the beginning of the planting season. Agents do not interact with each other, other than through the environment. Model results with regard to land-use patterns were validated in a previous study using remotely-sensed data (van Oel et al., 2010).

3.1.5. Initialization

For initial land use, data are used from 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

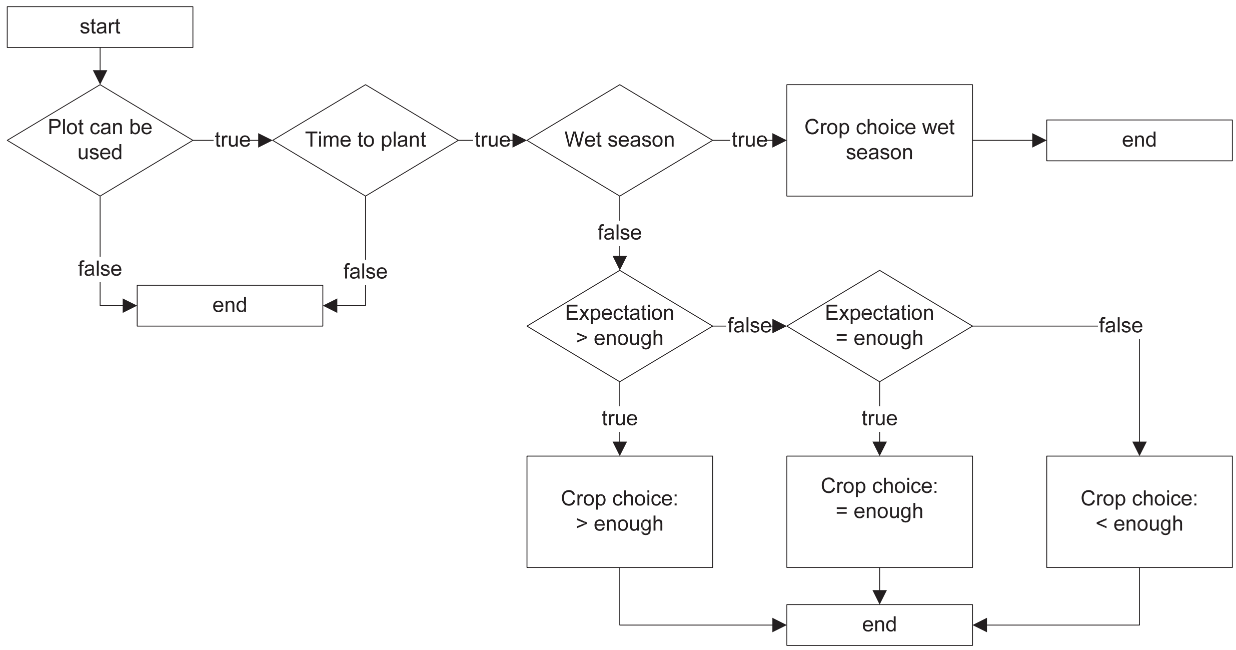

Fig. 3. Farmer land use decision flowchart. This flowchart applies to all agents, but the implementation of decision rules differs for the different agent types (van Oel et al., 2010).

Table 2
Rule implementation for different farmer types (van Oel et al., 2010).

Rule	River users	Floodplain users	Reservoir users
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 January 1st and April 10th or: date between July 1st and September 1st & at least 30 days after harvesting the wet season crop	Rainfall > 20 mm in 10 days & date between the January 1st and April 10th or: date between July 1st and September 1st & at least 30 days after harvesting the wet season crop	Date between January 1st and April 10th or: date between August 1st and December 31st
Wet season if:	January 1st–June 30th	January 1st–June 30th	January 1st–June 30th
Farmer expects more than sufficient water for the dry season if:	Rainfall during the wet season	Rainfall during the wet season	Reservoir volume at July 1st
	>Higher threshold	>Higher threshold	>70% of capacity
Farmer expects sufficient water for the dry season if:	Rainfall during the wet season	Rainfall during the wet season	Reservoir volume at July 1st
	>Lower threshold	>Lower threshold	>35% of capacity

(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. All grid cells that are equipped for irrigation are occupied by an agent. For agent preferences with regard to crop choice and the amount of land to irrigate data has been used from a survey conducted in 2006 among water users in the Jaguaribe valley (Taddei et al., 2008). In the period from May to August in 2006, interviews with 602 irrigation farmers in 149 localities (in 14 municipalities) of the Jaguaribe Valley were conducted. A random sampling method was used. For the ABSTRACT model the authors used data of 55 farmers that are located in the study area. For the survey, farmers were interviewed on their decisions with respect to land use for both the wet and the dry season. For the dry season, three qualitatively different situations were sketched to the respondents: a situation with water availability that is regarded as either less than sufficient; sufficient; or more than sufficient. In this study three scenarios have been used. The differences between these scenarios are described in Section 3.3.

3.1.6. Input

For an outlook towards 2050 a time-series is generated for meteorological parameters (rainfall and evapotranspiration) and upstream inflow into the study area (runoff). Use is made of meteorological data from the meteorological research institute of Ceará (FUNCEME, 2008) and the ECHAM4 climate model of the Max-Planck Institute, Hamburg, Germany. Downscaling of the model outcomes for the study area for the years 2000–2050 was done in the WAVES project (Gaiser et al., 2003), transforming regional climate data while remaining consistency with regional climate variability at inter-annual time scales (Werner and Gerstengarbe, 2003). Due to the spatial pattern of climate and climate change, upstream areas are confronted with the largest changes in this scenario. A summary of climate input parameters for the ABSTRACT model is given in Table 3. Soil characteristics are obtained from the database that was developed for the WAVES project (Gaiser et al., 2003). 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 the 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 runoff into the Trussu, Lima Campos and Orós were obtained from a study by Güntner (2002).

3.1.7. Submodels

A detailed description of the ABSTRACT model is presented in van Oel et al. (2010). A description of the water balance model is given in Section 3.2.

3.2. Water balance

A semi-distributed hydrologic modelling approach is used. The river is modeled by a sequence of branches, each of which depicts a part of the river including its underlying alluvial aquifer. Water is withdrawn from each branch and partly returns to it from the riparian areas. Some of these are irrigation areas that are composed of grid cells for which a water balance is simulated. For the water balance calculations soil and crop characteristics take into account (Table 1). Branches receive water from upstream branches and from riparian grid cells that provide runoff and return flows from irrigation (e.g. from drainage and seepage). Storage is arranged in alluvial aquifers and reservoirs. A schematic overview of the water balance in shown in Fig. 4.

Water demand by farmers in irrigation areas is determined using a modelling approach that is designed for a 10-day time step (Perez et al., 2002). External data are provided for rainfall (P) and potential evapotranspiration ($ET0$) values. The water balance of a grid cell is determined by the following mass conservation equation (all units in m^3/s):

$$\frac{\Delta S_{cell}}{\Delta t} = P + I - R_S - R_{SS} - ET \quad (1)$$

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 local water demands for irrigation (I) are determined at every time step.

For a river branch the water balance includes the underlying alluvial aquifer and is determined by the following mass conservation equation (all units in m^3/s):

$$\frac{\Delta S_{Ri}}{\Delta t} = \sum_{x=1}^{n} Q_{u,x} + \sum_{y=1}^{m} R_y - Q_d - W \quad (2)$$

where ΔS_{Ri} is the change in storage in the river branch over a time interval Δt, including the underlying alluvial aquifer, $Q_{u,x}$ 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 subcatchment, 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.

For a reservoir the water balance of a reservoir is determined as follows (all units in m^3/s):

$$\frac{\Delta S_{Re}}{\Delta t} = \sum_{x=1}^{n} Q_{u,x} + \sum_{y=1}^{m} R_y + P - E - Q_d - W \quad (3)$$

Table 3
Summary of climate input parameters for the ABSTRACT model.

Climatic parameters (average for area)	2001–2010	2011–2020	2021–2030	2031–2040	2041–2050
Average rainfall (mm)	877	822	911	752	594
Average ET0 (mm)	2084	2084	2046	2041	2093
Upstream inflow 1 (m^3/s)	32	22	21	12	9
Upstream inflow 2 (m^3/s)	0.9	0.4	0.6	0.2	0.1
Local runoff (m^3/s)	4.3	1.6	3.0	0.6	0.2

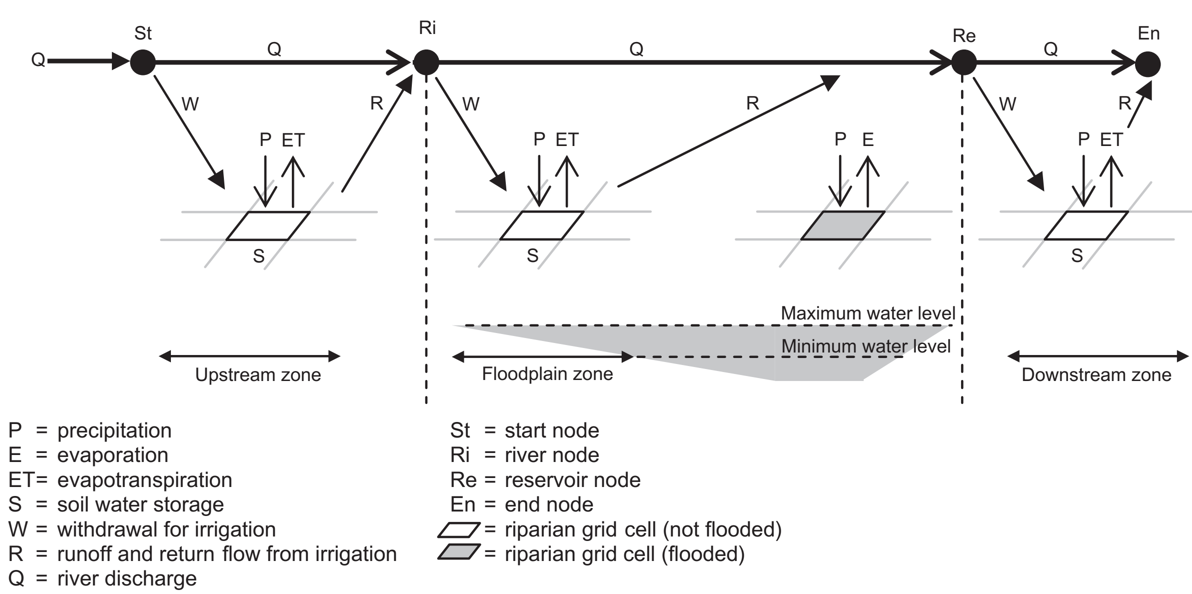

Fig. 4. Schematization of the water balance representation in the ABSTRACT model (van Oel et al., 2010).

Table 4
Description for the three scenarios for this study.

Scenario	Storylines	Study area implications	ABSTRACT parameter choices
1	– Concentration of water use for the irrigation of cash crops, tourism, and industry in the downstream valley of the Jaguaribe basin. – Water resources operated by centralized basin management.	– Target yield of main reservoir at a standard high (90% reliable[a]), based on historic inflow statistics van Oel et al. (2008).	– Main reservoir release: Wet season: 5 m^3/s Dry season: 20 m^3/s
2	– Water resources governed by local water management.	– Main reservoir is governed to serve local water users: stable dry season water level in main reservoir.	– Main reservoir release: Wet season: Water storage dependent: If volume < 76% of capacity: 0 m^3/s If volume > 76% of capacity: 5 m^3/s If volume > 95% of capacity: 15 m^3/s Dry season: 0 m^3/s
3	– Water resources governed by local water management – Additional infrastructure in the study area: more storage capacity, more irrigation	– Extra reservoir in main river upstream (capacity: 1×10^9 m^3) – Upstream irrigation system is designed according to that yield.	Same as for scenario 2 – New reservoir release: (local demand)[a] 2 + 3 m^3/s – Irrigated area increase in the upstream zone by 45%

[a] A 90% reservoir-yield reliability is in accordance with common Brazilian practice as described by Campos (1996) for designing reservoirs.

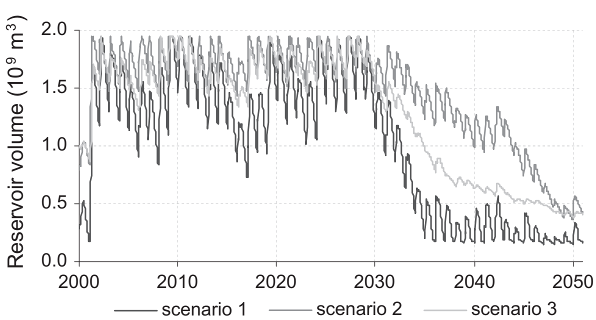

Fig. 5. Developments in reservoir volume in the main reservoir (Orós) for the three different scenarios.

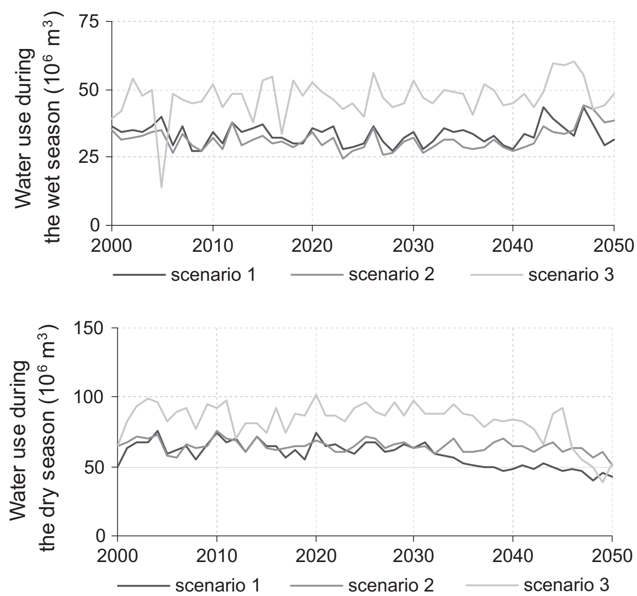

Fig. 6. Water use in the study area during the wet (top) and the dry (bottom) seasons for the three different scenarios.

where ΔS_{Re} is change in storage of the storage reservoir over a time interval Δt; $Q_{u,x}$ 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 subcatchment; 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).

3.3. Scenario approach

The ABSTRACT model is applied for three scenarios. These scenarios are local interpretations of other scenarios that have been designed for the states of Piauí and Ceará (Döll and Krol, 2002). The three scenarios that are used for this study are described in Table 4. In scenario 1 ("Coastal boom and cash crops" in Döll and Krol (2002)) water resources are managed in a centralized manner to serve downstream areas with urban or high-intensity irrigation uses. For reservoir operation a yield of 20 m^3/s during the dry season (and 5 m^3/s during the dry season) is applied. This corresponds to a reservoir-yield reliability of ~90% (van Oel et al., 2008). A yield reliability of 90% is the common design practice for reservoirs in the Northeast of Brazil (Campos, 1996). In scenario 2 ("decentralized development" in Döll and Krol (2002)) water management aims at a well-distributed regional development. In Scenario 2 local interest are better addressed by applying a very simple adaptive rule (Table 4) for reservoir operation. Although the threshold values are chosen arbitrarily, this rule represents a strategy that promotes a more stable water volume in the reservoir.

In scenario 3, an additional reservoir is installed at the upstream end of the study area to facilitate local development. With the new reservoir it becomes possible to retain water resources in the area. A reasonable storage capacity for such a reservoir is 1×10^9 m^3. The exact location of such a reservoir is not discussed. The same volume-surface relation as for the Orós reservoir has been assumed. The unchanged inflow into the area now flows into the new reservoir. The installation of the reservoir makes it more attractive for farmers to invest in irrigation infrastructure because of the more stable supply. Stabilization of upstream inflow both assures permanent supply and reduces flood risk in the floodplains of downstream reservoirs, in this case the midstream irrigation zone.

The spatio-temporal distribution of water is analyzed at two levels. Inside the study area developments with regard to water use in upstream, midstream and downstream zones are analyzed

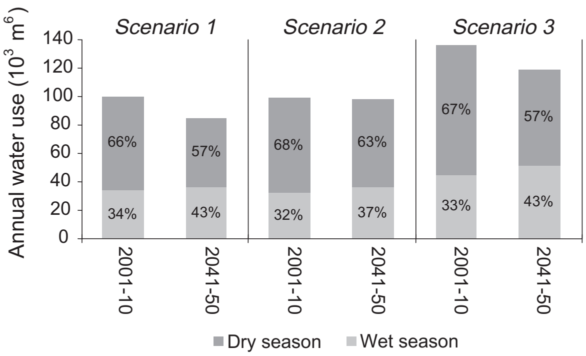

Fig. 7. Changes in annually-used water resources within the study area for the three scenarios.

and compared. At a higher level, on the one hand developments regarding the distribution of water resources that are used within the study area and on the other hand water resources that are available to users in the downstream valley through controlled yield from the main reservoir in the study area are compared.

4. Results

4.1. Developments in the seasonal distribution of water use

Fig. 5 shows the development of reservoir volume in the main reservoir within the study area. No dramatic differences between the three scenarios in reservoir volume are seen for the period 2001–2030. Between 2030 and 2050 the impact of changing meteorological parameter values becomes apparent for all three scenarios. The pattern of decline in reservoir volume is however different for each of the three scenarios (Fig. 5). An important factor in explaining why changes materialize after 2030 is that only beyond 2030 the meteorological pressure increases rapidly.

Water use in the study area shows a modest decrease towards 2050 for Scenarios 1 and 3, while it remains stable for Scenario 2. The dry season and the wet season show a distinctive picture. Wet season water use increases both absolutely and relatively when compared to dry season water use, which shows an absolute decrease in all three scenarios (Figs. 6 and 7). Wet season increases in water use are mainly explained by growing potential evaporation and declining rainfall rates, causing higher irrigation water demands. Dry season decreases in water use are related to lessening water availability in the dry season, which is amplified by the wet season increase in water use.

4.2. Spatial distribution of water use at the local level

Table 5 shows the relative shares of total water use the different zones for all three scenarios. Differences between the wet and the dry season are specified. Annual variation for 10-year periods decreases for Scenario 2 and increases for Scenario 3. From the simulation outcomes for Scenario 1, a relative transition of water use from downstream to upstream is observed. Decreases in water use are mainly experienced at the downstream end of the study area. Although users in the midstream zone also use less water, their relative share in total water use is maintained, as overall decline in water use is similar to the decline in water use by the users in the midstream zone. In Scenario 2 users in the midstream and downstream zones succeed in maintaining their water use levels because of a reservoir operation strategy that directly serves their interests. In Scenario 3 simulation outcomes show a relative transition of water use from upstream to downstream. Decreases in water use are mainly observed in the upstream zone, because the newly-built reservoir runs out of storage between 2041 and 2050. Water use in the downstream zone increases because of a more stable inflow from the main reservoir into the Lima Campos reservoir. Note that total water use inside the study area (Fig. 1) for that period is still considerably higher in Scenario 3 than in Scenarios 1 and 2 (Fig. 7). This is explained by the irrigation area that was added in the upstream zone. Although in both Scenarios 2 and 3 local interests are served by reservoir operation, overexploitation in Scenario 3 leads to increasing variability of water use when conditions become drier. This increase of variation is caused by supply failures in the upstream zone during the dry season, when water stress is highest.

4.3. Spatial distribution of water resources at the basin level

At the scale of the river basin the decreases in rainfall and runoff lead to diminishing water supply for the downstream valley in all

Table 5
Relative shares of water use in the different zones for all three scenarios. In Fig. 7 the overall change in water use for the study area is shown, specified by dry-season and wet-season contributions.

	Wet season water use		Dry season water use		Annual water use		
	2001–2010	2041–2050	2001–2010	2041–2050	2001–2010	2041–2050	Comment
Scenario 1							
Upstream zone	69%	61%	51%	65%	57%	62%	Relative transition from down- to upstream, mainly by dry season changes (downstream supply failure)
Midstream zone	8%	25%	30%	20%	23%	23%	
Downstream zone	23%	14%	19%	15%	20%	15%	
Coefficient of variation	0.13	0.14	0.10	0.07	0.09	0.09	
Scenario 2							
Upstream zone	72%	61%	49%	51%	56%	55%	No transition
Midstream zone	4%	18%	32%	28%	23%	24%	
Downstream zone	24%	21%	19%	21%	21%	21%	
Coefficient of variation	0.09	0.14	0.09	0.08	0.08	0.06	
Scenario 3							
Upstream zone	81%	72%	64%	63%	70%	67%	Relative transition from up- to midstream, because of wet season changes (upstream supply failure)
Midstream zone	3%	13%	23%	20%	14%	16%	
Downstream zone	16%	15%	13%	17%	16%	17%	
Coefficient of variation	0.25	0.14	0.08	0.27	0.12	0.19	

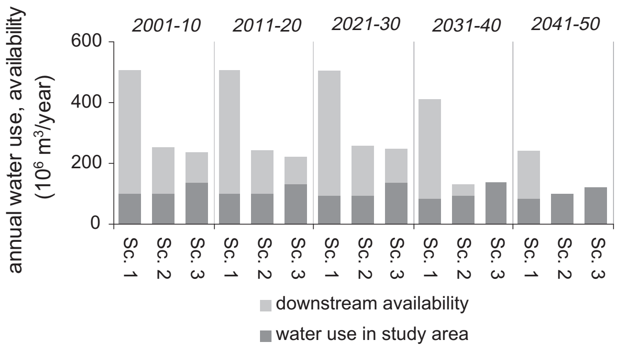

Fig. 8. Developments in annual water use within the study area and water available to water users in the downstream valley for the three different scenarios.

three scenarios, while a relative increase in upstream water use is seen (Fig. 8). In a situation with increased investments in storage and irrigation infrastructure in the study area (Scenario 3), water use in the area increases in comparison to Scenarios 1 and 2. The local expansion in water use produces an additional decrease in water availability in the downstream valley. Interestingly, for the period 2031–2050 total water use for Scenario 3 is higher than total water use for Scenario 2 (Fig. 8).

In a situation without spatial interventions in the study area (Scenarios 1 and 2), strategic reservoir operation is a powerful tool for water allocation. Under current meteorological conditions much water appears to be lost in case of Scenario 2, while high reservoir yield in case of Scenario 1 leads to relatively high water availability for the downstream valley. An additional advantage for users in the downstream valley in Scenario 1 is the timing of water supply: most of the water is released during the dry season (Table 4). Due to the reservoir-volume-related rule in Scenario 2 excess water is generally released during the wet season. Influenced by changing conditions for the period 2031–2050 relative advantages for water users in the study area become apparent. In effect a large externality is produced for the users in the downstream valley.

5. Discussion

Modeling choices with respect to threshold values for reservoir operation, farmer decision making and the size of the infrastructural investments for Scenario 3 certainly influence simulation outcomes. However, although the extent and timing of events are certainly affected, the outcomes for the three different scenarios do not change qualitatively.

The climatic input data that have been used have also influenced the simulation outcomes. For this study a climate scenario with a large reduction in rainfall and consequent runoff values was used. The goal of this study is to explore the influence of reducing rainfall and runoff in a realistic way, not to accurately predict future circumstances.

Empirical survey data on water user responses to variations in water availability have been used in the model. It was assumed that water users would respond in a similar way to structural decreases of rainfall and runoff as they do to the current rainfall and runoff regime.

Although the scenarios cover a period of 50 years, no developments other than climatic changes were taken into account. Important factors that potentially influence water use and water availability are demographic developments, market variations, institutional changes, governmental interventions and technological developments affecting for example pumping capacity and irrigation efficiency.

The reservoir operation strategies that have been implemented in the ABSTRACT model are merely representing operation according to the reservoir-yield reliability at the design of the reservoir (Scenario 1) or reactive to changes in the environment (i.e. reservoir volume in Scenarios 2 and 3). In practice, reservoir operation in the Jaguaribe basin depends on decisions made by a complex process with a combination of local and supra-local authorities and local users or user representatives involved. Although it may be possible to represent this kind of decision making it is believed that models like the ABSTRACT model may be beneficial in supporting such decision making processes, rather than in representing them. Promising examples of using multi-agent simulation for decision support on a local scale have been provided by researchers who apply the so-called 'companion modeling approach' (Bousquet et al., 2007; Barreteau, 2003).

6. Conclusions

This study shows that a decrease in rainfall and runoff in the Jaguaribe basin leads to a transition of water use from the dry to the wet season. As a net result water scarcity in the dry season increases. Because of lower rainfall and runoff values annual water use within the study area remains stable or decreases slightly towards 2050, depending on the reservoir operation strategy applied. For all three scenarios wet season water use within the study area shows an absolute as well as a relative increase. Water use in the dry season decreases as a result of reduced rainfall and runoff. It declines even further because of a decrease in water availability during the dry season through increased water use in the wet season.

For all scenarios, a decrease in rainfall and runoff in the Jaguaribe basin leads to a relative transition of water use from downstream to upstream on the basin scale, clearly indicating that river basin closure (Molle et al., 2010; van Oel et al., 2011.) is taking place. With models like the ABSTRACT model this process can be studied in further detail.

This study shows that by applying alternative reservoir operation strategies and by building additional reservoir capacity water managers are able to offset the effect of lower rainfall and runoff values with regard to water use on the subbasin level, at the cost of decreasing water availability at the basin level. Within the study area (subbasin scale) a relative transition of water use from downstream to upstream has only been observed for a scenario in which the reservoir operation strategy aims at producing high and stable water supply for the valley downstream of the study area (Scenario 1). When the reservoir operation strategy aims to serve subbasin interests, a situation without such a transition (Scenario 2) or with the opposite transition (Scenario 3) can be achieved at the subbasin level.

Acknowledgements

We thank Nicolas Becu for important contributions in the first stages of model implementation. The ABSTRACT model is inspired on the CatchScape model (Becu et al., 2003). Further we thank Alex Pfaff, Kenneth Broad, Valerie Muller, Upmanu Lall and Julio Hercio Magalhaes Cordeiro for allowing us to use records of respondents of a survey carried out in the period from May to August in 2006, funded by the NOAA Office of Global Programs (Taddei et al., 2008). Field visits in 2005 and 2006 were made possible by the Netherlands Organization for Scientific Research (NWO).

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