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Application of MAS to depict spatiotemporal interdependencies between water use and water availability in a semi-arid river basin

Van Oel, P.R.[1]

[1]*Department of Water Engineering and Management, University of Twente, PO Box 217, 7500 AE Enschede, the Netherlands*
Email: p.r.vanoel@utwente.nl

Abstract: This study addresses the interactions between water users and water resources and describes the application of a Multi-agent simulation (MAS) model that has been developed to improve understanding of the processes that drive changes and variations in the spatial and temporal distribution of water resources in a semi-arid river basin. These processes include hydrological processes and water user responses to variations and changes in water availability. The results are relevant for climate change impact assessments, spatial planning and river basin management, in particular for water allocation in semi-arid environments. The MAS model represents water users that both respond to and modify the spatial and temporal distribution of water resources in a river basin. Farmers' decisions on irrigated area and crop type are simulated on the basis of rules including factors such as rainfall, anticipated water availability and observed water availability. Local water abstractions for irrigation influence natural water flows and, reversely, the distribution of water resources over space and time influences water abstractions. Model validity and the use of survey data for representing the studied system dynamics are discussed. It is concluded that a multi-agent simulation model offers a good opportunity for representing the interdependencies between water availability and water use in river basin areas where irrigated agriculture is an important water user. The model can be used for exploring the emergence of basin closure and its relation to water-scarcity patterns. This study shows that a decrease in rainfall and runoff in the Jaguaribe basin in the northeast of Brazil leads to a transition of water use from the dry to the wet season. The dry season water use decreases because of reduced water availability in the dry season. This 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 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 respect to water use at the sub-basin scale, at the cost of further decreasing water availability at the basin scale.

Keywords: *river basin, water scarcity, irrigation, multi-agent simulation (MAS), climate change*

1. INTRODUCTION

In spite of rapidly improving insights, many questions that are related to the impacts of climate change on water availability, water use and interdependencies between these two in semi-arid river basins remain unanswered. In this paper, these questions are addressed by analysing and modelling the interaction between water users and water resources and by assessing how this interaction affects the spatial and temporal distribution of water availability and water use in a semi-arid river basin. The relation between water users and water resources is mutual: human interference in hydrological processes changes water resources availability and changes and variations in the distribution of water resources over space and time induce response by water users. Although many important studies (e.g. climate change impact assessments) recognise that one should take into account impacts of human activities on natural processes for studying water scarcity, water user responses to variations and changes in water availability are generally not taken into account for designing models that support spatial planning and decision-making on water allocation in semi-arid river basins.

It is increasingly acknowledged that multi-agent simulation (MAS) is an adequate modeling technique for representing human-environment interactions in a spatially explicit way (Matthews et al., 2007; Parker et al., 2003). Some MAS applications have been developed to analyze and support water resource management for irrigation schemes and sub-basins (Barreteau et al., 2004; Becu et al., 2003; Berger et al., 2007; Schlüter and Pahl-Wostl, 2007). Berger et al. (2007) show that MAS is a promising approach for supporting water resource management and to better understand the complexity of water use and water users within sub-basins.

The objective of this study is to increase understanding of the influence of changes and variations in rainfall and the application of alternative reservoir operation strategies on the spatial and temporal distribution of water availability and agricultural water use in a semi-arid river basin. This is achieved by analysing and modelling the interactions between water users and water resources. A MAS model has been developed and validated. The river basin that was used for empirical evidence in this study is the Jaguaribe basin in the northeast of Brazil.

2. STUDY AREA

The Orós reservoir study area is located inside the Jaguaribe basin, Ceará, Brazil (Figure 1). The capacity of the Orós reservoir is around 1.9 $10^9 m^3$. Current annual precipitation ranges from 450 to 1150 mm 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, inter-annual variability, seasonal variability and variability at the time scale of a week (*e.g.* Gaiser et al., 2003).

Water use is dominated by abstractions for irrigation. Water management and water abstractions for irrigation are intensely discussed in Ceará because of persistent pressure on water reserves in strategic reservoirs (*e.g.* COGERH, 2003; Lemos, 2003; Van Oel et al., 2008)

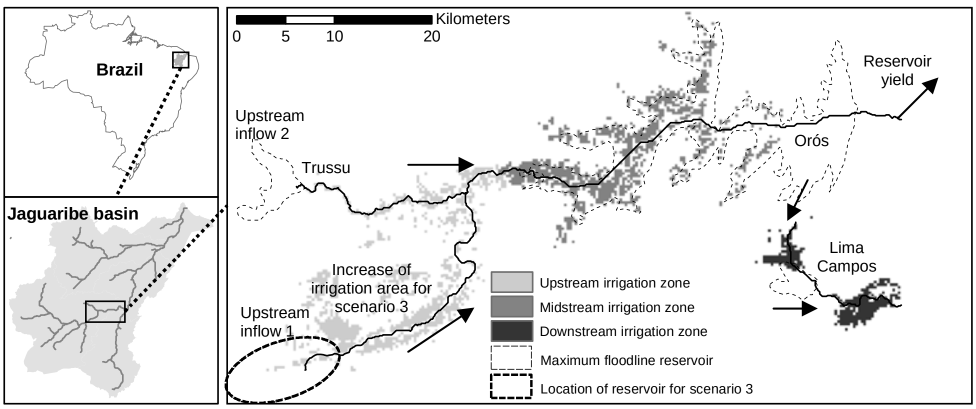

Figure 1. Orós reservoir study area: the different irrigation zones are labelled upstream-, midstream-, and downstream irrigation zone.

3. METHOD

3.1 The ABSTRACT model

The ABSTRACT model (Agent Based Simulation Tool for Resource Allocation in a CatchmenT) is designed and tested for the Orós reservoir study area, in which surface water reservoirs have been installed, in which the irrigation sector is an important water user and in which there are possibilities of multi-annual water allocation. The ABSTRACT model was developed with the CORMAS platform using the VISUALWORKS environment (Bousquet et al., 1998). For representing feedback processes between water availability and water abstractions for irrigation, topographical elevation, hydrological characteristics, storage and abstraction of water resources have been included. Model output includes the spatiotemporal distribution of water availability and water use.

In the ABSTRACT model, agents represent farmers that are situated at specific geographical locations and make decisions followed by actions affecting the environment. The model applies a 10-day time step. The modelling 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 calculated.

The biophysical dynamics involve vertical and horizontal water balance calculations. A semi-distributed hydrologic modelling approach has been used (Figure 2). The main river is represented by a network of branches. Each branch represents a part of the river including the underlying alluvial aquifer. From each branch, water is withdrawn and water returns from riparian areas. Among these areas are irrigation areas that consist of grid cells for which the vertical water balance is simulated. 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.

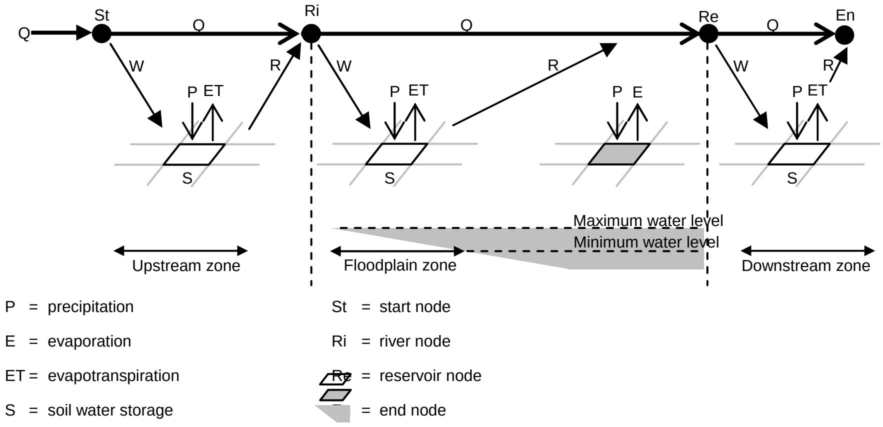

Figure 2. Schematisation of the connection between the horizontal and the vertical water balance.

Land use decisions are made by individual farmer agents that take into account local conditions and preferences. Three different locations with respect to access to sources of irrigation are distinguished: upstream of a reservoir; on a reservoir floodplain; and downstream of a reservoir. Land use decisions are followed by actions implementing the decisions. Harvesting takes place when crops are ready to be harvested, or harvests are lost by flooding. Every time step, land availability is updated according to water levels in reservoirs and land cover changes due to harvesting. Accessibility of sources for irrigation and flooding of agricultural fields are taken into account in describing farmer 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). Farmers in the area generally cultivate riparian plots with an area of between 5 and 10 hectares (COGERH, 2003). The grid cell size of our model is 7.29 hectares, corresponding to nine grid cells of the digital elevation model (DEM) with grid cell size of 90×90 m2 that has been used (EMBRAPA, 2006). For the elevation of the cells in the ABSTRACT model the value of the middle cell of squares composed out of 9 DEM grid cells has been taken. Rules for farmer decision-making that take into account flood risk and limitations with respect to 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. 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. For specific rule implementation and details on the data that were used for the ABSTRACT model, see Van Oel et al. (submitted).

Validating simulation outcomes for the seasonal volume changes of the Orós reservoir are quite good (Figure 3). Simulation outcomes for land use variations (irrigated area) compare reasonably well to land use classification outcomes of remotely sensed data for the dry seasons during the period 2000-2005 (Figure 4).

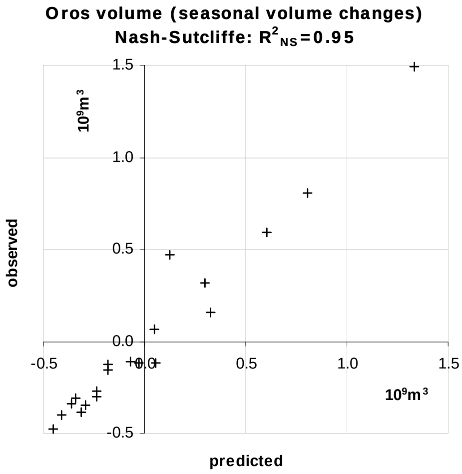

Figure 3. Observations and predictions of seasonal volume changes in the Orós reservoir for the period 1996-2005. Each year has two seasons: wet (January- June) and dry (July-December).

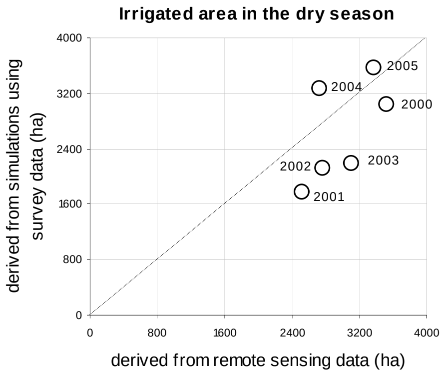

Figure 4. Comparison between outcomes for irrigated area as a result of ABSTRACT simulations (based on survey data) and land use classification for remotely sensed data.

3.2. Assessing the effect of decreasing rainfall and reservoir operation strategies

With the ABSTRACT model the influence of decreasing rainfall and alternative reservoir operation strategies on the distribution of water use and water availability in the Jaguaribe basin is assessed. Three scenarios with respect to reservoir operation and spatial planning are designed (Table 1). These scenarios are local interpretations of two scenarios that have previously been designed for the states of Piauí and Ceará, in which the Jaguaribe basin is located (Döll and Krol, 2002). For generating a time series of upstream inflow (runoff) and meteorological parameters (rainfall and evapotranspiration), use is made of downscaled results from the ECHAM4 climate model (Roeckner et al., 1996). Downscaling for the period 2000-2050 was done during the WAVES program (Gaiser et al., 2003).

Table 1 Description of the three scenarios for this study

Scenario	Storylines	Study area implications	ABSTRACT parameter choices
1	- Concentration of water use in the downstream valley of the Jaguaribe basin. - Water resources operated by centralised basin management.	- target yield of main reservoir at a standard high (90% reliability), based on historic inflow statistics	- 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.	- Main reservoir release: same as for scenario 2 - New reservoir release: (local demand) * 2 + 3 m^3/s - Irrigated area increase in the upstream zone by 45%

The distribution of water use is analysed at two spatial scales. Inside the study area, developments with respect to water use in upstream, midstream and downstream locations are analysed and compared. At a larger scale, the study analyses changes in the distribution of water resources that are used inside the study area on the one hand and water resources that are available to users in the downstream valley through controlled yield from the main reservoir in the study area on the other hand.

4. RESULTS

4.1 Developments for the seasonal distribution of water use

During the first 30 years of simulation (2001-2030), no dramatic changes in rainfall, potential evaporation and discharges are represented in the climate input data series. Therefore no dramatic shifts in water availability and water use are expected to result from none of the three scenario simulations. Changes are expected after 2030, when meteorological pressure increases rapidly. During the period between 2030 and 2050 the impacts of changing meteorological parameter values become apparent for all three scenarios. The pattern of decline of reservoir volume is however different for the three scenarios.

Water use in the study area shows a modest decrease towards 2050 for scenario 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 absolute and relative when compared to dry season water use which shows an absolute decrease for all three scenarios (Figure 5). Wet season increases of water use are mainly explained by increasing potential evaporation and decreasing rainfall rates causing higher irrigation water demands. Dry season decreases of water use are related to decreasing water availability in the dry season which is amplified by the wet season increase of water use.

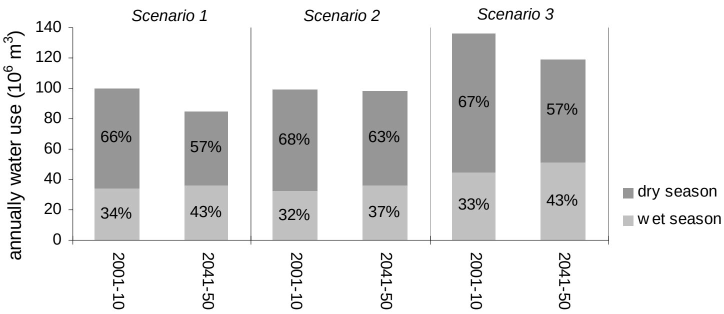

Figure 5. Changes in annually utilised water resources inside the study area for the three scenarios.

4.2 Spatial distribution of water use at the local scale (inside the Orós reservoir study area)

From the simulation outcomes for scenario 1 a relative transition of water use from downstream to upstream is observed. Losses of water use are mainly experienced at the downstream end of the study area. Users in the midstream zone also experience considerable absolute losses, however, their relative share in total water use is maintained. For scenario 2, users in the midstream and downstream zones succeed in limiting losses because of a reservoir operation strategy that directly serves their interests. For scenario 3, simulation outcomes show a relative transition of water use from upstream to downstream. Losses are mainly felt in the upstream zone, because the newly installed 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 for that period is still considerably higher for scenario 3 than for scenarios 1 and 2. This is due to the irrigation area that was added in the upstream zone.

4.3 Spatial distribution of water resources at the basin scale

At the scale of the river basin the decreases in rainfall and runoff lead to decreasing water supply for the downstream valley for all three scenarios (Figure 6). At the basin scale a relative increase of upstream water use has been encountered.

For a situation with unchanged spatial interventions in the Orós reservoir study area (scenario 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 relative high water availability for the downstream valley. An additional advantage for users in the downstream valley in case of scenario 1 is the timing of water supply. Most of the water is released during the dry season. In case of scenario 2, excess water is generally released during the wet season. Under influence of changing conditions for the period 2031-50, relative advantages for water users in the study area become apparent. A large externality is produced in effect for the users in the downstream valley.

For a situation with increased investments in storage- and irrigation infrastructure in the study area (scenario 3), water use in the Orós reservoir study area increases in comparison to scenario 1 and scenario 2. The local increase of water use produces an additional decrease of water availability in the downstream valley. Interestingly, for the period 2031-50 total water use for scenario 3 is higher than total water use for scenario 2 for the same period.

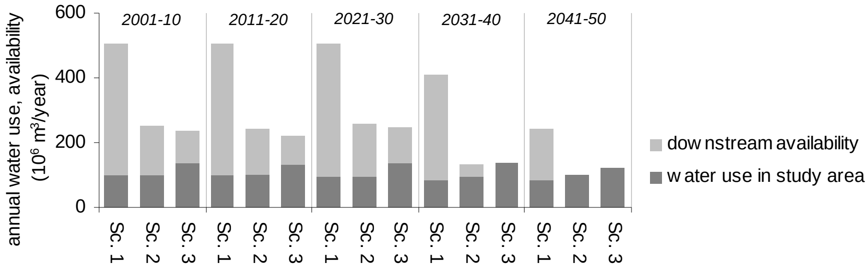

Figure 6. Developments in annual water use inside the Orós reservoir study area and water available to water users in the downstream valley

5. DISCUSSION

Direct validation of the model outcomes with respect to water abstractions was not possible due to a lack of available data on water use. However, land use classifications of remote sensing data offered good opportunities to validate the simulation of land use, being the main determinant of water abstraction in the ABSTRACT model. Decision-making heuristics with respect to 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 of remote sensing data for the study area. Resemblance is best for farmer groups with well identifiable water sources on which they depend. Representing heterogeneity of farmer decision-making based on the available survey data was not possible for the local scale, since exact geographical locations of agricultural activities were unknown.

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, the simulated developments for the three different scenarios are not very sensitive for these choices in a qualitative sense although the extent and timing of certain impacts obviously are.

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

For the model that was used in this study, empirical survey data for water user responses to variations in water availability have been used. It was assumed that water users would respond similarly to structural decreases of rainfall and runoff as they do for 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 include demographic developments, market variations, institutional changes, governmental interventions and technological developments influencing e.g. pumping capacity and irrigation efficiency.

6. CONCLUSIONS

For the Jaguaribe basin, a representation of processes that are responsible for observed variations in the distribution of water use and water availability can be made by applying a spatially-explicit multi-agent simulation model approach that is implemented by using survey data on water user decision-making. The model could serve as a learning tool for authorities and resource users and facilitate improved decision-making on water allocation and spatial planning. The added value of the MAS approach that has been presented in this paper, if compared to standard approaches (e.g. pattern-oriented, stochastic approaches), is that it allows for evaluating the spatiotemporal effects of the interactions between individual water users and water resources on water scarcity patterns at different spatial and temporal scales.

For the Jaguaribe basin, wet season water use increases with decreasing water availability, whereas dry season water use decreases with decreasing water availability. This implies that for years with below-average rainfall the increased water use during the wet season may amplify water stress in the following dry season. Improvements in the understanding of the relationship between water use and water availability in a semi-arid river basin have been achieved by taking into account water user responses to variations in water availability. The interactions between water users and water resources are specifically important for understanding the distribution of water resources over space and time.

Decreases in rainfall and runoff influence the temporal and spatial distribution of water availability and water use. More in particular, decreasing rainfall typically leads to transitions of water use from water-scarce periods to less water-scarce periods and from downstream areas to upstream areas. To offset the effects of decreasing rainfall and runoff, water managers can apply reservoir operation strategies to manipulate temporal and spatial distribution of water resources in sub-basins. This can only be achieved at the cost of water availability in parts of the basin that are located further downstream.

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