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ORIGINAL ARTICLE

Economic water management decisions: trade-offs between conflicting objectives in the sub-middle region of the São Francisco watershed

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Abstract
Hydro-economic models can measure the economic effects of different reservoir operating rules, environmental restrictions, maintenance of ecosystems, technical constraints, institutional constraints, land use change, and climate change. To determine the optimal economic water allocation, for its main uses in the sub-middle of the São Francisco River Basin, a hydro-economic optimization model was developed and applied. Demand curves were used rather than fixed requirements for water resources. The results show that operation rules of reservoirs and institutional constraints, such as priorities for human consumption, have high impacts on costs and benefits of the principal economic uses in the study area. Especially, costs of environmental demands, like minimum ecological river flow, have high impacts on the water resource management. Scarcity costs of irrigation users associated with maintaining ecosystems and environmental constraints are particularly significant. The results from this study provide a better understanding of the water trade-offs for future policymaking and efficient water management. Policymaking for the water resources should consider the food-water-energy-environment nexus at a regional scale to minimize environmental and economic cost under water scarcity and land use change.

Keywords Hydro-economic model · Water allocation · Land use change · Water resource management

Introduction

The semi-arid region of Brazil is increasingly affected by water scarcity while economic growth boosted by the agricultural sector relies heavily on water for irrigation. Population and income growth are creating a growing demand for water in non-agricultural sectors and non-rural areas. Temporal and spatial variability of rainfall and high evaporation rates, along with prolonged droughts, characterize the region. Climate change and continued population growth may further increase the existing water problems. The overexploitation of available water resources and the use of storage reservoirs also affect the quality of fresh water supplies by causing impacts such as salt water intrusion. Furthermore, environmental demands of economic development are increasing, which will impact the use of water resources.

The sub-middle basin of the São Francisco River (SMSF) was selected for the development and application of a hydro-economic water allocation model. Hydro-economic models are important to evaluate the economic costs and benefits associated with water uses and can identify the economic optimum water allocation between different users. The results of such models can measure the economic effects of environmental restrictions, maintenance of ecosystems, and institutional constraints. The model results are useful to decision-makers for establishing policies that create appropriate incentives for efficient resource use and preventing overexploitation, while assisting in the promotion of sustainable development. The hydro-economic model uses demand curves instead of a fixed demand for water. Markets for natural resources, such as the water market, are often absent or ineffective and

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water resource allocation decisions can rarely count on the autonomous functioning of the market. Instead, demand curves and marginal water values should be used to support policy interventions in order to prevent overuse of the resource and ensure good quality (Alcoforado de Moraes et al. 2010; Harou et al. 2009; Maneta et al. 2009; Mayer and Muñoz-Hernandez 2009).

Torres et al. (2012) presented a linked hydro-economic model and applied it to the São Francisco River Basin, with the aim of analyzing effects of water use regulations and product price changes for agriculture, based on the work of Maneta et al. (2009). The work focused on changes for the agriculture sector and aimed to understand impacts of water use regulations on irrigated agriculture. This paper analyzes the trade-offs between environmental demands, hydropower, water supply by public utilities, and irrigated agriculture.

Methodology

Study case

The study area is located in the semi-arid region of Brazil, which has particular characteristics, especially with respect to climate and vegetation. The semi-arid climate in Brazil is characterized by irregular spatial distribution and concentration of rainfall which often results in water scarcity. In this semi-arid region, annual average rainfall varies from a minimum of 400 mm to a maximum of 800 mm per year. The dry season is prevalent and can last up to 11 months in the areas of greater aridity. Precipitation occurs irregularly and in a concentrated form spanning 2 to 3 months of the year, during which time heavy precipitation (120–130 mm in 24 h) can be observed (EMPRAPA 2008; MIN 2005). Irrigation accounts for about 70% of total water withdrawals within the sub-middle São Francisco basin. Incentives involving higher prices of water for irrigation are increasingly being seen as an effective tool to reduce water demand.

One of the main water users, the Hydroelectric Company of São Francisco (CHESF), built several large dams in the SMSF, mainly for the purposes of hydropower generation and multi-year flow regulation. The largest reservoir (Sobradinho) has a water surface area of 4214 km^2 and a maximum volume of 34,117 hm^3 (ONS 2014). It is one of the largest artificial reservoirs in the world. The Sobradinho Reservoir has the most significant hydrological impact on the SMSF and the water uses downstream. The Itaparica (Luiz Gonzaga) Reservoir downstream has a capacity of 10,782 hm^3. Other pass-through reservoirs/dams used for hydropower generation downstream from the Itaparica Reservoir are the Paulo Afonso complex, Moxotó, and Xingó.

Significant consumptive water users are irrigation projects and small farmers in proximity to the São Francisco River. Over 19 irrigation projects of various sizes are located in the SMSF. Currently, the largest irrigation project, Nilo Coelho, has an area of about 22,061 ha and presents a yearly water demand of 350,543,462 m^3 (ANA 2011). Climate change and land use change could increase the demand for irrigation water. Several new irrigation projects and channels are planned. Figure 1 shows the study area and the principal present and possible future irrigation projects.

Developing the hydro-economic model

To simulate the water availability within the hydro-economic model, hydrologic data for the selected periods was used from the soil and water integrated model (SWIM) (Krysanova et al. 1998; Krysanova et al. 2000). SWIM is an eco-hydrological model of steady and spatially semi-distributed flow. The model was developed from SWAT models (Arnold et al. 1993) and Matsalu (Krysanova et al. 1989) to evaluate the impacts of land use and climate change. SWIM simulates hydrological processes, growth of vegetation, erosion, and nutrient dynamics at a river basin scale (Koch et al. 2013) and has been applied to the watershed of the São Francisco River (Koch et al. 2015a).

MAgPIE (Model of Agricultural Production and its Impact on the Environment) is a global, spatially explicit, economic land use model (Biewald et al. 2014; Lotze-Campen et al. 2008). This model has been used in order to project crop-specific agricultural land use patterns while taking into account the impact of global socioeconomic changes such as population growth, trade liberalization, and changes in overall dietary patterns. Alcoforado de Moraes et al. (2018) obtained economic values of water for irrigated agriculture production for present and future irrigation projects in the SMSF using MAgPIE projections.

The hydro-economic model was developed in GAMS (General Algebraic Modeling System), a modeling platform for programming mathematical problems, which is especially useful for problems of optimization. This platform can solve linear and non-linear programming problems and is particularly useful for solving large, complex problems such as those involving a large number of variables and constraints or a high degree of non-linearity (Rosenthal 2012). The developed model is a deterministic process-based continuous simulation model based on "perfect foresight." This signifies that the results are obtained with the perfect knowledge of the future, more specifically, the availability of water during studied time periods. The periods must be representative in terms of hydrological conditions of the studied region, and the results provide an upper (optimal) limit of the system. The use of hydro-economic models allows us to measure the trade-offs between uses, water shortage costs, and benefits, along with shadow prices of institutional and environmental constraints under discussion such as those established by Koch et al. (2015b).

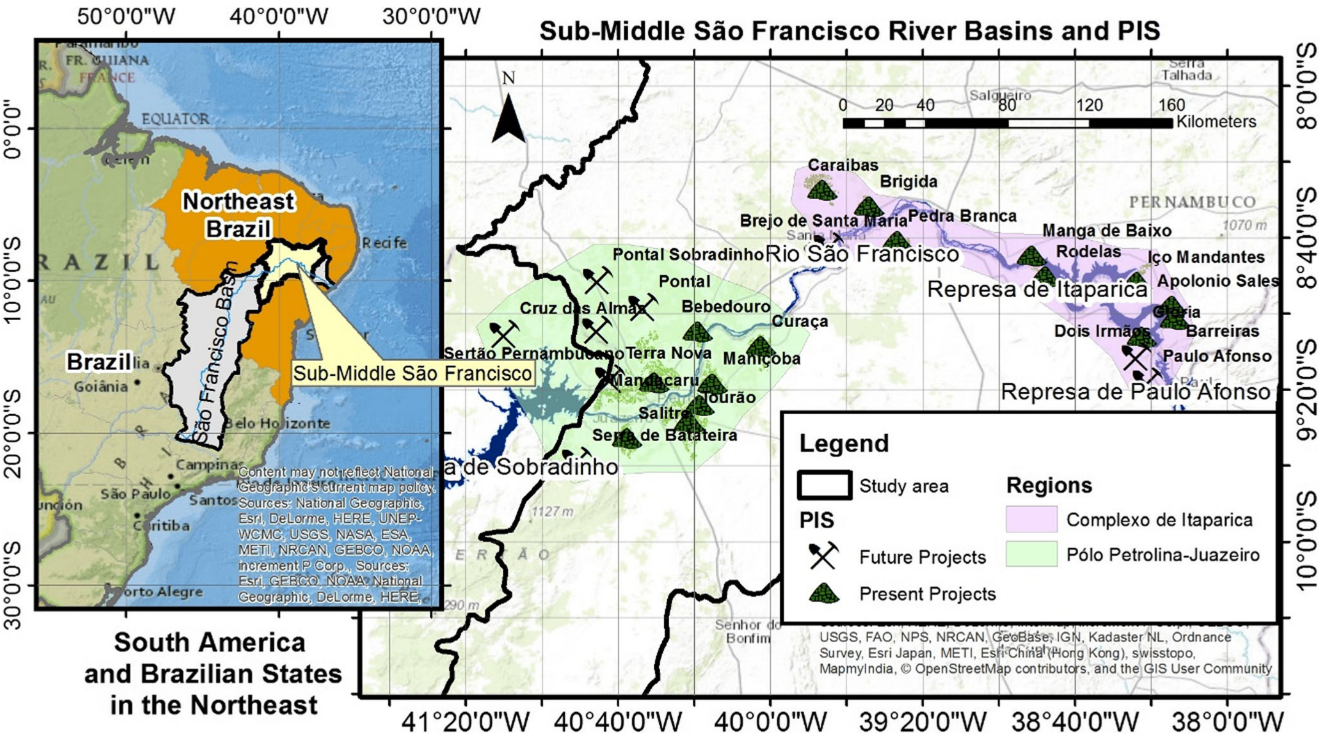

Fig. 1 Study area with irrigation projects

The model is based on the graph theory, in which the water transport is simulated through a directed graph. A representative network of the hydrologic system is used, which includes the flow resulting from the upstream river basins (tributary nodes), reservoirs (reservoir nodes), river sections (river nodes), and users (user nodes). For each type of node, a given mass balance is performed, depending on its nature. The inflow is calculated as the sum of all inflows from all nodes upstream of the node in question, using SWIM data. The withdrawal of water for consumptive uses is diverted from the river or reservoir nodes to the user nodes. For irrigation uses, the demand comes from the PMP (demand curves obtained by Positive Mathematical Programming) using census data and in the case of future demands using MAgPIE data. Figure 2 shows how the different inputs are connected to the hydro-economic model (graph theory) and the principal nodes.

Demand curves

The measure of the responsiveness of the quantity demanded of a good to changes in its own price is known as price elasticity of demand (Lipsey 1988). To estimate the demand function for water resources, which measures the marginal benefits associated with various amounts of the resource, data is needed on the total quantity of the resource as well as the economic benefits associated with it. There are many ways to use water, either for direct or indirect use in a production process, such as food production, or for basic ecosystem services. Due to this diversity in the use of water resources and its specific features, a variety of methods to estimate the economic demands for water have been developed and continue to develop (Booker et al. 2012). In general, econometric methods require extensive and reliable data series.

Demand curves for existing and future governmental irrigation projects and small farm irrigation sites were obtained by using Positive Mathematical Programing (Alcoforado de Moraes et al. 2018; Souza da Silva and Alcoforado de Moraes 2015). Methods for obtaining demand curves through PMP are based on a certain price and estimate the amount of water that maximizes farmers' profits. From different amounts of allocated water, gains or losses in producers' profits and the economic value of water are estimated. This information is used to represent the derived demand for irrigation water. The adopted elasticity of substitution for all crops and regions was 0.5, as was used in Maneta et al. (2009) and Torres et al. (2012). For the supply elasticity of the crops, we used 0.2. In general, the base economic values of water associated with the different supply elasticities are the same. The data consisted of a total of 11 crops (banana, sugarcane, onion, coconut, guava, mango, passion fruit, watermelon, melon, grape, tomato) for 15 irrigated regions. Several assumptions are made about the yield response function of irrigation water, such as a constant elasticity of substitution for the production function for agricultural producers as used in the study by Medellín-Azuara et al. (2010). This production function restricts the extent to which one input can substitute another. The use of 0.5 signifies a medium rate of substitution

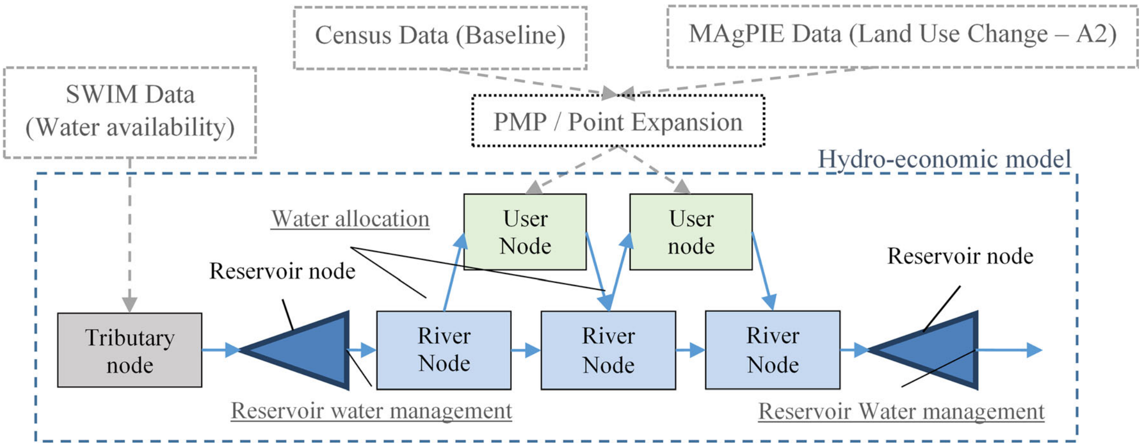

Fig. 2 Hydro-economic model: network and model interactions

among production factors which can represent the production technology in regions such as the SMSF. For the cost function calibration, the quadratic functional form with the mentioned supply elasticity (0.2) of the crops was also used as in the referenced papers. For the future, the irrigated areas of each irrigation project were downscaled and calibrated for the SMSF, using simulation results from the global land use model MAgPIE, as described by Alcoforado de Moraes et al. (2018); the data used for MAgPIE and PMP can be found in the supplementary material of this paper. Figures 1 and 2 in the supplementary material show the demand curves for governmental irrigation projects in the baseline period and under the A2 scenario, respectively.

For the water supply of the municipalities, demand curves were obtained by Souza da Silva et al. (2015) using the point expansion method with an adaptation proposed by Alcoforado de Moraes et al. (2006). The point expansion method has been used in numerous studies and is an important tool for estimating demand (Griffin 2006; Harou et al. 2009). The method is relatively easy to apply, as all demand curves are obtained using only one known point in the function (usually the current operating point) and the price elasticity of demand, which is exogenous and assumed to be constant (Griffin 2006; Varian 2006).

Land use and climate change scenarios

A 7-year period (2000–2006) has been selected to represent the hydro-climatologic conditions and land/water use in the study area for which the optimal economic allocation will be obtained. The constraints used are technical, socioeconomic, and environmental. Data from this period represent an initial set (baseline) used to compare changes in operating rules, constraints, climate change, water availability, and land use changes. Furthermore, economic impacts of different water allocation strategies were analyzed by changing the constraints in the model.

To evaluate the impact of land use and climate change, the A2 scenario was used as described in the Special Report on Emission Scenarios (Nakicenovic and Swart 2000), which represents a regionalized world with slow economic development as well as high population growth and little awareness of environmental problems. MAgPIE results show that land use for agriculture will double in 2035 as compared to 2005. For changes in existing and new planned irrigation projects (Fig. 1), demand curves were generated by Alcoforado de Moraes et al. (2018) using PMP and were implemented in the hydro-economic model using polynomial regression.

With reference to water availability, Figure 3 in the supplementary material shows the inflow to the Sobradinho Reservoir (main contributory and regulatory reservoir for the SMSF) for the two studied time periods. One is the historical time period (2000–2006) and the other is the HadGEM RCP8.5 (Madec and Imbard 1996) projection for 2034–2040. Both selected periods represent time series that include some years of below-average inflow (2850 $m^3\ s^{-1}$ (CBHSF 2004)) to the Sobradinho Reservoir to address risk and water scarcity caused by climate variability. The average inflow in the period from 2000 to 2006 is 2168 $m^3\ s^{-1}$ and from 2034 to 2040 is 2656 $m^3\ s^{-1}$. The HadGEM model shows a more humid future; therefore, the selected period shows higher water availability in comparison to the present. The land use, withdrawals, and management of the upstream basin are already included in the SWIM in both periods using the same scenarios.

Initially, only essential operational and some institutional constraints were used to determine the economic optimum in the periods as a reference. The restrictions included the physical/technical, flood control (ONS 2014) and institutional: the minimum outflow Sobradinho > 1300$m^3\ s^{-1}$ and Xingó > 1300$m^3\ s^{-1}$ (CBHSF 2004). The objective function minimizes the scarcity cost for irrigation sites, small farmers, and human consumption, as well as the difference between electricity generation and the guaranteed electricity generation for each hydropower plant with the PLD (settlement of price differences). At the same time, the objective function maximizes the economic benefit of electricity production. Equation (1) shows the objective function (OF).

$$\mathrm{OF}=\mathrm{Minimize}\left(\sum_{n\in \mathrm{pi}}\sum_{a}\sum_{m}C_{n,a,m}+\sum_{n\in \mathrm{id}}\sum_{a}\sum_{m}C_{n,a,m}+\sum_{n\in \mathrm{ah}}\sum_{a}\sum_{m}C_{n,a,m}-\sum_{n\in \mathrm{ener}}\sum_{a}\sum_{m}B_{n,a,m}+\sum_{n\in \mathrm{ener}}\sum_{a}\sum_{m}\left(E_{\mathrm{secured}(n)}-E_{n,a,m}\right)^{2}\cdot \mathrm{PLD}\right) \quad (1)$$

where:

- n User: pi (irrigated area), id (diffuse irrigation), ah (supply), ener (electricity)
- C Scarcity cost (R$)
- B Benefit user (R$)
- E Electricity generation (MW)
- a, m Year, month
- PLD Settlement of price differences (see the "Hydropower generation" section)

Scarcity costs (C) of consumptive water uses in Eq. (1) are calculated by using the demand curves, approximated from the economic values obtained by PMP, using a polynomial regression, with Q being the amount of water allocated in thousands of cubic meters. In the hydro-economic model, the gross benefit lost between the quantity allocated and the total demand is used to calculate the scarcity cost, by integrating the demand curves. The scarcity costs function can be seen in Eq. (2), where Q is the quantity of water allocated in thousands of cubic meters and a_k are the regression constants:

$$C(Q)=\int_{Q_{\mathrm{aloc}}}^{Q_{100}}\sum_{k=0}^{4}a_kQ^k\,dQ \quad (2)$$

Benefits for electricity generation (B) in Eq. (1) are calculated directly by using the hydraulic head, turbine-specific head losses, and electricity prices (PLD). Major model parameters, variables, equations, and restrictions (institutional and environmental constraints) can be found in the supplementary material.

The model represents a relatively simple approach for water resource management, which uses numerous variables and inputs from other models (SWIM, MAgPIE). To address risk, some uncertainties can be addressed, principally regarding data deficiencies. For water availability, uncertainties are mainly due to unknown exact water withdrawals by users upstream of the study area and real losses within the Sobradinho Reservoir (seepage, real evaporation). These uncertainties were addressed and discussed by Koch et al. (2013). Higher uncertainties are related to costs and benefits of consumptive water users in the present and even more in the future scenarios. Assumptions made for economic parameters have a high influence on water allocation; Figure 11 in the supplementary material shows, for example, the influence of price elasticity variation on the marginal benefits for consumptive water users.

Constraints and changes in operating rules

Constraints and changes in operating rules were analyzed in relation to impacts on water users and net benefits/costs of those changes. One analyzed scenario prioritizes human consumption, which uses the same restrictions as in the previous scenario, but with priority for human consumption as provided by the Brazilian Federal Law 9433 (Brasil 1997). Another scenario is the implementation of the São Francisco River Transboundary Project (PISF), which is a project of the Brazilian Federal Government whose implementation, operation, and maintenance are the responsibility of the Ministry of National Integration. The PISF is designed to ensure water supply for the semi-arid region of four states in the north of Brazil's Northeast (Paraíba, Pernambuco, Rio Grande do Norte, and Ceará). Two hydraulic systems are being built (north and east axes) and will be operated and maintained by the Development Company of the Parnaíba and São Francisco Valleys—CODEVASF (Brasil 2006; Castro 2011). Average withdrawals of the Transboundary Project are simulated in this scenario to assess the economic impacts on the "donor" basin. Furthermore, we analyzed water supply systems for municipalities without losses, because water supply systems for the municipalities in SMSF show high losses. In this scenario, the demand curves are changed to consider the supply of municipalities without losses in order to measure the economic impact of the losses for other water uses and users. The same restrictions as in the previous stage were used to evaluate the costs/benefits for the system.

The construction of reservoirs in the São Francisco River has changed the natural flow in the dry and wet seasons. There are some approaches to provide more environmentally friendly flows/reservoir management for sustaining ecosystem services downstream and within the reservoirs while simultaneously considering human demands. For the Lower-Middle São Francisco River, an environmental hydrograph was suggested (Ferreira 2014; Medeiros et al. 2013) which proposes monthly target values of flow in the river downstream of the Xingó reservoir to make the conditions in the Lower São Francisco River more ecologically favorable to natural processes. This includes natural cycles of aquatic plants and animals, and social processes of stakeholders, users, and institutions. Table 1 in the supplementary material shows the values of the proposed environmental hydrograph.

Alternative operating rules were suggested for reservoirs focusing on environmental aspects, with the goal of balancing ecosystem and anthropogenic water demands (Koch et al. 2015b). In the level control option, the water level variations are reduced to a maximum of 1.5 m/month, restricting the maximum monthly volume of water to be released in each reservoir. In addition, the level variation was reduced to a maximum of 12 m and, to reduce evaporation of Sobradinho Reservoir, the maximum level was restricted to 390.0 m, reducing the live capacity to 19,479 hm^3. Reducing the daily variations in the reservoir water level increases the stability and maintenance of ecosystems. In the same study, Koch et al. (2015b) analyzed other changes in the live capacity. For the Itaparica Reservoir, an operating option was suggested restricting the water level variations to a minimum and maximum of 303.5 and 304.0 m. For Sobradinho, variations of the maximum reservoir level were restricted to the minimum and maximum values of 388.5 and 389.0 m. By restricting variations in the water level to these dimensions, evaporation losses can be reduced significantly while the hydraulic pressure head is not greatly reduced. This restriction also serves to increase the stability and maintenance of reservoir ecosystems.

The Water Resources Plan of the basin of the São Francisco River provisionally set a minimum ecological flow of 1300 $m^3 s^{-1}$ at the outlet of the river. The committee recommended further studies and the adoption of a system of seasonal (periodic) streamflow in the Lower São Francisco for the maintenance of ecosystems (CBHSF 2004). The reduction in downstream flow of Sobradinho below the minimum flow has recurrently been practiced due to water scarcity and has had significant impacts on the operation of reservoirs and other uses.

Hydropower generation

Hydropower generation is a non-consumptive water user; however, costs/benefits are created within the reservoir management and downstream releases (reservoir evaporation and water availability downstream). Demand, benefits, and prices are directly related to electricity generation and the electricity market. Electricity prices tend to be a reflection of the times and react to factors such as periods of drought, the global geopolitical background that affects the price of oil, or even an internal economic policy of the country. At this time, there is no competitive market for electricity generation from the hydropower dams in the SMSF because governmental contracts and laws secure payments simply by providing the electricity generation capacity of the hydroelectric dams run by CHESF (Brasil 2013, 2015). Therefore, we used PLD values (settlement of price differences), which represent the amount to be paid for short-term electricity. For example, the portion that the company failed to produce as established in the contract must be obtained in the SPOT market (electricity market for immediate delivery) or generated as excess to be sold in the SPOT market to other companies that have generated an amount below what was set in their contracts. However, these prices do not contain surpluses/deficits over the years for the company (CHESF). Figure 4 in the supplementary material shows a scatterplot comparing stored volume in the Sobradinho Reservoir and PLD values from 2003 to 2016 for Brazil's Northeast. The storage of the Sobradinho Reservoir presents a good proxy for drought periods and related increases in electricity prices in the Northeast. Prices tend to increase with lower water storage in the reservoir. The selected scenario periods present years with below-average rainfall/runoff; therefore, an initial fixed average economic value of 400 R$/MWh was set for the electricity generation and the estimated PLD value was used for the difference between produced electricity and firm electricity.

Results

The shadow price of the outflow of the Sobradinho Reservoir (main reservoir for flow regulation) shows the effect of costs and benefits in the objective function if an additional unit (1 m^3 of water) is released downstream of the reservoir. The results show that the main impact for the shadow price is the water availability during the simulated periods. In dry periods, the shadow price of Sobradinho release increases. Even though, the incorporation of environmental hydrograph and level control rules also result in a notable increase of the shadow price of the Sobradinho downstream water release. Absolute values for shadow prices under the different scenarios can be found in Figure 12 in the supplementary material. Shadow prices for the water release from Sobradinho do not change very highly if key parameter assumptions for consumptive users are altered (e.g., demand elasticities), because the water quantity used for ecological flow/hydropower (e.g., min flow 1300 $m^3 s^{-1}$) is much higher than the allocation for irrigation (e.g., 51.9 $m^3 s^{-1}$ in the baseline scenario). Hydropower, with its high benefits, low costs, and ecological constraints, controls the model sensitivity in this case study.

Baseline scenario

Reference

The baseline-reference results show how the model responds without additional constraints for the years 2000–2006 and without prioritizing any water use or user. Figure 5 in the supplementary material shows the stored water and the outflow of Sobradinho Reservoir during the studied period (baseline-reference scenario). It can be observed that the model uses almost the full live capacity of the reservoir; past observations show less usage of the live capacity of the reservoir, mainly because of the perfect foresight of the model, which the operator does not have. Observed differences in the reservoir water storage management as overprediction in the beginning (drought period) and underprediction (wet period) differ mainly due to the already mentioned perfect foresight. For example, the model knows about the 4-year drought period; therefore, the model reduces the outflow of the Sobradinho Reservoir already in the first year to a minimum to keep the electricity generation at a higher and constant level. The opposite occurs in the wet period, dominated by the objective function for maximizing benefits for hydropower production.

The minimum flow of 1300 $m^3 s^{-1}$ downstream of Sobradinho and at the outlet could be guaranteed during the entire period (considering that the firm electricity was not a restriction). Figure 6 in the supplementary material shows the electricity generation of the Sobradinho Reservoir within the simulation period. The firm electricity (dotted line) cannot be reached by the electricity generation of the reservoir during periods with less water availability. The net benefit from the electricity generation is R$46.61M (Sobradinho/Itaparica) and R$144.72M for the Moxotó, Paulo Afonso, and Xingó complex for the simulated period from 2000 to 2006. All results in this section are given as aggregated net benefits/costs for the simulated 7-year period.

A noticeable result in the reference scenario can be seen in Figure 7 in the supplementary material, which shows the allocation of water for the city of Petrolina. It can be observed that the allocation of water for human consumption occurs only in periods with high water availability, as no restriction for prioritizing human consumption was considered in this scenario. Due to high water distribution losses associated with low direct economic benefits compared to other uses (agriculture and electricity production), the amount allocated for human supply is reduced. This can also be seen in the low scarcity cost for the municipality, which only accounts for R$27.25M in this scenario.

Most irrigation projects and small farmers have less water allocated to them during dry seasons. Figure 8 in the supplementary material shows the water allocation for the irrigation sites Nilo Coelho, Salitre, Barreiras, and Tourão. Only the irrigation project Tourão consistently had 100% of its water allocated. High yields and low water-related costs result in high economic values and therefore more allocated water. Overall, water allocation for irrigation is reduced and scarcity costs are accepted in favor of other uses and more water is allocated for irrigation sites in periods of higher water availability. The overall scarcity costs for irrigation sites are R$238.42M.

Constraints and operating rule scenarios

Using the scenario that prioritizes human supply (considering the existing high distribution losses of treated water) as guaranteed by the Brazilian law, the scarcity costs of irrigation users increase 2.61% for small farmers, and 1.25% for irrigation projects, relative to the baseline values obtained without priorities for human consumption. Economic benefits of electricity generation are slightly reduced (0.03%) for Sobradinho/Itaparica hydropower plants and by 0.04% for Paulo Afonso/Moxotó/Xingó hydropower plants. The results for human supply without distribution losses show a higher water allocation for domestic users during periods of higher water availability (Figure 7 in the supplementary material); however, scarcity costs are still present and no water is allocated for domestic users in periods with lower water availability. When including the SF Transboundary Project, with an average withdrawal for both axes as a fixed average (16.4 $m^3 s^{-1}$ north channel and 10 $m^3 s^{-1}$ east channel), scarcity costs further increased over 6.91% for small farmers (retaining the priority for human consumption). Scarcity costs increased 8.64% for irrigated projects compared to the previous level and benefits from hydropower were again reduced as compared to previous values (priority for human consumption): − 0.61% for the Sobradinho/Itaparica hydropower plants and − 0.94% for the hydropower plants of the Paulo Afonso and Moxotó complex.

Environmental demands have the highest impact for users in the SMSF. Figure 9 in the supplementary material shows the stored volumes and releases during the simulation period, comparing storage and release, with the minimum outflows using the environmental hydrograph and the 1300 $m^3 s^{-1}$ restriction (baseline). The electricity generation of the Sobradinho Reservoir within the simulation period shows that the environmental hydrograph restriction reduces the electricity generation notably in dry seasons. Additionally, results predominantly show that the water allocation for irrigation is reduced to provide water for the environmental hydrograph. The other analyzed environmental restrictions have even higher impacts on costs and benefits in the SMSF. Table 1 shows the changes in scarcity costs and benefits for all constraints and operating rule scenarios in relation to the reference scenario.

Scenario A2 with climate change

Reference

The results for the future scenario A2, including MAgPIE land use change projections and climate change represented by the new demand curves (used from this point on), show substantial alterations for irrigation projects. However, because of higher water availability, the scarcity cost for irrigation projects decreases to R$182.1M for the simulated period (2034–

Table 1 Baseline result comparison

Changes in costs/benefits (%)	Priority municipality supply	Transboundary Project SF	Human supply without losses (allocation)	Human supply without losses, 100% allocation	Environmental hydrograph	Level control	Reduced capacity	Sobradinho outflow min. 1100 $m^3 s^{-1}$
Scarcity costs human supply			− 11.7					
Scarcity costs small farmers	+ 2.86	+ 6.91	+ 1.94	+ 2.74	+ 39.9	+ 46.9	+ 58.8	+ 2.60
Scarcity costs irrigation projects	+ 0.43	+ 8.64	+ 1.40	+ 2.73	+ 40.0	+ 41.9	+ 63.5	+ 1.96
Benefits Sobr./Itaparica	− 0.04	− 0.85	+ 0.01	0.00	− 1.34	− 6.73	− 7.79	− 0.01
Benefits Moxoto, PA	− 0.05	− 0.98	+ 0.01	− 0.01	− 1.30	− 6.07	− 8.98	− 0.02
Shadow price outflow Sobradinho	− 34.7	7.37	− 35.4	− 34.8	765.1	1432	2499	− 87.5

2040) and water allocation for irrigation projects increases. Figure 10 in the supplementary material shows the water allocation for the irrigation projects already shown in the baseline scenario (Nilo Coelho, Salitre, Barreiras, and Tourão). One possible explanation for why the allocation for the Salitre irrigation project is higher (along with differences in economic values of both projects) is that the Nilo Coelho water withdrawal is upstream from the Sobradindo hydropower plant, and therefore, the Nilo Coelho irrigation project competes more with electricity generation than the Salitre irrigation project.

The benefits of the Sobradinho/Itaparica hydropower plants in this scenario are R$50.12M, primarily due to the higher water availability in comparison to the baseline scenario, which presents an increase of 7% in hydropower production. For the hydropower reservoirs in the Moxotó, Paulo Afonso, and Xingó complex, a small increase (1%) is observed resulting from the increased demand for irrigation water in the SMSF basin. Net benefits of these reservoirs are R$143.61M. The average overall electricity generation nearly achieves the secured electricity demands in this period. The irrigation sector results are presented in Table 2, which shows the allocated water for the irrigation projects in comparison to the baseline scenario. Water allocation increases differently for irrigation projects.

The comparison of the Petrolina, Juazeiro, and Itaparica regions shows how different irrigation regions are impacted by different water allocations. Table 3 compares water allocation and scarcity costs for the three irrigation regions. The Petrolina region has a higher water allocation due to higher economic benefits in the future scenario. In the baseline scenario, Juazeiro has higher productivity and relatively low costs, including water, compared to Petrolina. Therefore, the economic value of water is higher and more water is allocated. The irrigation projects within the Itaparica region have the lowest economic values and therefore receive less water in both scenarios.

Constraints and operating rule scenarios

Due to the higher water availability in this scenario, the cost for environmental demands decreases in comparison to the baseline scenario. For the environmental hydrograph, almost no additional costs for electricity generation are created in comparison to the A2 reference scenario (− 0.3% benefits for all hydropower dams). The shadow price of the Sobradinho outflow and benefits for electricity generation are only slightly changed. However, irrigation users still have a substantial increase of scarcity costs (+ 19%), though this cost remains less than in the baseline scenario (+ 40%). The level control option benefits for hydropower decrease (− 10.4% Sobradinho/Itaparica and – 9.3% Moxoto/Paulo Afonso) and irrigation scarcity costs increase + 192%. Model results for the reduced capacity scenario show a decrease of 8.5% in electricity generation benefits for Sobradinho/Itaparica and − 9.5% for Moxoto/Paulo Afonso. Scarcity cost for irrigation increases drastically (> 20 times in relation to the reference scenario) due to artificially created lower water availability in certain years. Furthermore, the shadow price of the Sobradinho release increased greatly because of the relatively low reference shadow price.

Discussion

The developed hydro-economic model was able to satisfactorily represent the observed past reservoir management (Baseline), considering that no operational rules of the reservoirs were introduced (aside from flood protection and minimal outflow limits). The model is quite simple and depends on

Table 2 Water allocation (%) for irrigation projects (baseline and scenario A2 with climate change)

PIS	Municipality	Baseline (%)	Scenario A2cc (%)
Cruz das Almas/Sertão Pernambucano	Casa Nova		100
Pontal Sobradinho/Terra Nova/Pontal	Petrolina		100
NiloCoelho	Petrolina	96	98
Bebedouro	Petrolina	96	100
Serra da Bat.	Juazeiro		100
Salitre	Juazeiro	96	100
Mandacaru	Juazeiro		95
Maniçoba	Juazeiro	95	100
Tourão	Juazeiro	100	100
Curaçá	Juazeiro	96	100
Brejo de Santa Maria	Santa Maria da BV		100
Caraibas	Santa Maria da BV	95	98
Brigida	Orocó	95	97
Pedra Branca	Curaçá	94	100
Rodelas	Rodelas		93
Barreiras	Petrolândia	93	95
Icó-Mandantes/Apolônio Sales	Petrolândia	95	95
Gloria	Glória		98
Dois Irmãos/Paulo Afonso	Glória		100

other models, like SWIM, for the rainfall runoff determination. All results from the hydro-economic model have an associated level of uncertainty that varies in magnitude. For the model itself, which mostly performs a monthly water balance on a small scale, the uncertainty is relatively low in comparison to more complex hydrological/economical models which use more parameters and assumptions. The uncertainty depends mainly on the quality of the input data from global and downscaled regional models, like MAgPIE and SWIM. Not considered or unknown water withdrawals of irrigation users will impact results for reservoir management and water allocation. Demand curves aggregate many inputs and assumptions (e.g., price elasticities), but give a good and robust indication regarding water use efficiency and criteria for water allocation. In the future, the model can be extended with other features such as water quality parameters. The inclusion and adaptation of new features is relatively simple in the GAMS environment, which makes the model flexible for water resource analyses. In this work, the impacts of water scarcity were analyzed in a suitable time scale regarding different scenarios of water supply and demand. With this approach, it was possible to identify the economic costs of the management rules for multiple uses and to identify trade-offs between conflicting objectives, such as environmental demands, irrigation, and hydropower generation.

Table 3 Water allocation (%) per region

Region	Baseline (%)	Scenario A2 (%)	*Δ* (%)
Petrolina	96	100	3.71
Juazeiro	97	99	2.42
Itaparica	95	97	2.86

The climate change scenario analyzed does not show extended drought periods in the future and indicates decreasing stress for the users and water allocation, while land use change will increase water demand. Results show that with more irrigation projects installed, the demand for water becomes more competitive. The competition for water between the irrigation projects increases. Water allocation reflects the economic value of water for the user; high yields and low costs favor water allocation for irrigation schemes. Hydropower, with its high benefits and low costs, has a major impact on water allocation for other uses but also depends on electricity pricing.

The results show that scarcity costs of ecosystem services and environmental constraints are relatively high and have major impacts (increasing scarcity cost) mostly for irrigation users. In addition, institutional constraints, such as priorities for human consumption, minimum downstream release, limits for reservoirs, and water provided for the SF Transboundary Project, impact the costs and benefits of the two main economic sectors (irrigation and power generation) in the SMSF. Scarcity costs for irrigation users generally increase more (in terms of percentage) than for the other users, for the environmental and institutional constraints. Additionally, droughts have high economic and environmental cost. Kahil et al. (2016) stated, for example, that ecosystem protection requires policy intervention and the regulation of cooperation's by public agencies, in order to reduce scarcity costs. Macian-Sorribes et al. (2015) concluded that scarcity-based pricing policies are one of the most promising solutions for efficient water usage.

The variation of the shadow price of the downstream release from Sobradinho Reservoir, i.e., the effect of costs and benefits in the objective function if an additional unit (1 m^3) is released downstream of the dam, shows that most impacts have institutional and environmental demands (SF Transboundary Project, environmental hydrograph, level and reduced capacity control), besides the water availability during the simulated period. Shadow prices are elevated because the introduction of such restrictions results in increases in scarcity costs and reductions of benefits for the two main economic sectors (irrigation and hydropower). The shadow prices tend to increase the economic value of water released from Sobradinho in situations of greater scarcity and reflect the expectation of increasing additional releases. It is important to note that this increase occurs in the aggregated costs of the uses represented in the objective function, which does not prevent some of the uses from having their scarcity costs reduced with the release. Moreover, the benefits of environmental uses were not represented in the objective function nor were the benefits of economic sectors linked to municipal supplies (economic sectors like commerce and services). Where a priority of human supply is guaranteed, additional releases from Sobradinho have lower economic value as compared to the reference because the scarcity costs of human supply were excluded. Lowering the minimal release limit from Sobradinho shows that the shadow price is also reduced relative to the reference, thus confirming that from the reference release level (lower limit 1300 m^3 s^{-1}), additional releases increase the total scarcity costs in the region. Liu et al. (2008) also concluded that the shadow price is not only a reference for water price; the shadow price also reflects water scarcity.

The future scenario used for the region shows increased demand for agriculture and higher future economic value of water. Together with less water availability, one can expect higher scarcity costs of agriculture in relation to ecological demands. Therefore, the use of other climate change models is also recommended; for example, the MIROC model projects a dryer climate for the study region. This could increase scarcity costs for irrigated agriculture, derail ecological demands, and increase conflicts with hydropower production. Different operating constraints of the reservoirs, currently defined by the electricity sector, can be simulated in the model along with new water availability scenarios and evaluated using benefits and costs for all users. Those results can support policymakers on decision-making or adjusting current plans under consideration of economic and environmental costs, as also recommended by several researchers (Min et al. 2017; Siegmund-Schultze 2017; Zeng et al. 2016).

The water demand curves used in the scenarios were established using current economic water values collected in the basin (production costs, crop water requirements, crop mix) for the current irrigation users and future projections of land use change and climate change. The adjustment of water-related costs (e.g., higher water prices) supports the implementation and adjustment of public policies related to management of water resources in the region and the evaluation of economic outcomes in relation to new climatic conditions. Economic impacts of environmental and institutional constraints on current and future scenarios, obtained by hydro-economic modeling, should assist in decisions for implementation of water resource management instruments in the region.

Conclusion

Understanding the relationship between multiple water demands, climate conditions, and environmental requirements supports the planning of measures to promote a good economic and ecological water allocation. Policymaking for the water resources should consider the food-water-energy-environment nexus at a regional scale to minimize environmental and economic cost under water scarcity. The results from this study can provide a better understanding of the water trade-offs for future policymaking and efficient water management.

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