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Proposition of a hydro-economic model applied to the water conflict in the Alto São Marcos to optimize water allocation

Proposição de um modelo hidroeconômico aplicado ao conflito hídrico no Alto São Marcos para otimização da alocação de água

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ABSTRACT: The use of water as the main input for agricultural and livestock production and electricity usually reveals conflicts between the demanding sectors when it is relatively scarce. In this scenario, the conflict in the Alto São Marcos basin is notable in Brazil due to the inefficiency of meeting the demand for water for the irrigation and electric sector, involving the national domain, the states of Minas Gerais, Goiás, and the Federal District. Thus, the objective of this work is the construction and application of a hydro-economic model that optimizes the allocation of water between these sectors and has as a parameter the economic value of the resource defined by the maximization of intersectoral profits. The methodology employed was inspired by the works proposed by Fujisawa (2016) and Silva (2017), using non-linear programming under the contour conditions of Karush-Kuhn-Thucker (1951) in a deterministic scenario. An objective function is proposed that minimizes the operational cost of a scarcity of irrigated perimeters while maximizing the economic benefit of energy production. The data used are derived from ANA (National Water Agency) regulations and the hydroelectric plant's operating history made available by ONS (National System Operator) and CCEE (Electric Energy Trading Chamber). From the results obtained, there was a reduction in the value of water for irrigators, considering the value once delimited by the real dynamics, under the equivalent availability of inputs, an indication of the efficiency of the proposed seasonal dynamics. However, despite the economic rationale inserted, the reproduction of the prioritization of use for the irrigating sector, within the established limits, penalized the remuneration and generation of Batalha HPP. Thus, the aim is, through modeling, to contribute to the measurement of the economic effects of the negotiated allocation of water.

Keywords: hydro-economic model; water allocation; São Marcos River; economic value of water; water conflict; nonlinear programming.

RESUMO: O uso da água como principal insumo para a produção agropecuária e de energia elétrica costuma revelar conflitos entre os setores demandantes quando é relativamente escassa. Neste cenário, notabiliza-se, no Brasil, o conflito na bacia do Alto São Marcos, devido à ineficiência de atendimento da demanda por água para o setor irrigante e elétrico, envolvendo o domínio nacional dos estados de Minas Gerais, Goiás e do Distrito Federal. Assim, o objetivo deste trabalho é a construção e aplicação de um modelo hidroeconômico que otimize a alocação de água entre estes setores, e tenha como parâmetro o valor econômico do recurso definido pela maximização de lucros intersetoriais. A metodologia empregada foi inspirada nos trabalhos propostos por Fujisawa (2016) e Silva (2017), utilizando programação não linear sob as condições de contorno de Karush-Kuhn-Thucker (1951) em um cenário determinístico. Propõe-se uma função objetivo que minimiza o custo operacional de escassez dos perímetros irrigados ao passo que maximiza o benefício econômico da produção de energia. Os dados utilizados derivam dos normativos da ANA (Agência Nacional de Águas) e do histórico de operação da hidrelétrica disponibilizado pelo ONS (Operador Nacional do Sistema) e pela CCEE (Câmara de Comercialização de Energia Elétrica). A partir dos resultados obtidos, verificou-se redução no valor da água para os irrigantes, considerando o valor outrora delimitado pela dinâmica real, sob a equivalente disponibilidade de insumos, indicação de eficiência da dinâmica sazonal proposta. Contudo, apesar de a racionalidade econômica inserida, a reprodução da priorização do uso para setor irrigante, dentro dos limites estabelecidos, penalizou a remuneração e a geração da UHE Batalha. Assim, busca-se, com a modelagem, contribuir com a mensuração dos efeitos econômicos da alocação negociada de água.

Palavras-chave: modelo hidroeconômico; alocação de água; Rio São Marcos; valor econôomico da água; conflito hídrico; programação não-linear.

1. Introduction

The use of water as the main input for agricultural production and electricity usually reveals conflicts between these two demanding sectors, when it is relatively scarce, and requires efficient management of its supply. This panorama rekindles the debate about improving the dynamics of water uses, the dialogue between sectorial policies and the applicability of economic instruments in the allocation of water.

Although Brazil is privileged in its water supply, its demand is not evenly distributed with the availability of the resource considering the physical, economic, political, and social aspects of this continental country, as highlighted by the Survey of Irrigated Agriculture by Central Pivots in Brazil (ANA, 2019).

In this scenario, several conflicts over the use of water resources have taken place in the national territory in recent years, such as the conflict in the Alto São Marcos between the irrigating and electric sectors. Such conflict is structured in the São Marcos River, a federal river belonging to the hydrographic basin of the Paranaíba river, between the irrigators of the states of Minas Gerais, Goiás, Federal District, and Union, which mostly use the central pivot technique, and the Batalha hydroelectric power plant (HPP) belonging to the National Interconnected System (SIN).

The São Marcos River was selected by the National Water and Basic Sanitation Agency (ANA) as one of the 26 National Poles, special areas for the management of water resources for irrigated agriculture on a national scale, according to Ordinance No. 1,082 / 2019 / MDR, of April 25, 2019 (MDR, 2019), which establishes the Federal Government's Irrigated Agriculture Poles initiative, as presented in ANA (2020). As greater relevance is attributed to the central pivots of the region, the concession for the generation of electric energy granted to the Batalha HPP is a conditioning factor, which limits the flow of consumptive uses upstream of it until the year 2040, when is the end of its concession to Furnas Centrais Elétricas SA Company.

The rivalry of uses brings up the discussion about the compatibility of water consumption for irrigation with the reserve of water availability for hydroelectric generation, in addition to the economic rationality applied in a scenario of prioritization of uses. Faced with this challenge, the application of hydro-economic models emerges as a tool capable of resolving the trade-off between uses, measuring economic effects of intersectoral policies, and adding economic rationality to water allocation.

Thus, the objective of this work was to propose and apply a hydro-economic model that optimizes the allocation of water between hydroelectric generation and irrigation in the Alto São Marcos water conflict and takes as a parameter the economic value of water defined by maximization of intersectoral profits.

2. State of the art

The report on climate change, water and economics published by the World Bank Group (2016) recognizes the "expanded water nexus", in which the fortunes of the food, energy, cities and environment sectors are linked by a common dependence on water. In addition, the report outlines three comprehensive policy priorities that can help guide countries on the path to an economy with water security and climate resilience: optimizing water use through better planning and incentives; expanding water supply and availability, where appropriate; and reducing the impact of extreme weather events, their variability and uncertainty. As for the optimization of water use, it is highlighted that better ways of allocating water among sectors for uses with higher value can be achieved through planning and regulation or by market signals, including economic instruments such as marketable prices and licenses. In both cases, with safeguards to guarantee access to water for poor families and farmers, as well as the environment. It should be noted that the fundamentals of economic management instruments are present in the Dublin Principles (ICWE, 1992), in the National Water Resources Policy (Brasil, 1997) and in the World Water Forum (GWP, 2000), and are presented as complementary devices to traditional models.

It should be noted that, when approach the water theme, it is important to clarify the conceptual difference between water and water resources. Granziera (2006) clarifies that water is a natural element of our planet, as well as oil, and therefore has no economic value. It is only from the moment it becomes necessary for a specific destination for human activities that water becomes a resource because it is economically valued. Thus, Lemos & Lemos (2009) complements that water is a genus, an environmental asset of diffuse interest, while water resources are species. Therefore, it must be differentiated that in the law, water is classified as a public good, whose national domain belongs to legal entities of internal public law that must manage the good to benefit all those who need it, whereas in the microeconomics, the water is considered a private asset because it does not have characteristics of non-rivalry and non-exclusivity. Such conceptual differences guide and permeate this work in the search to add greater economic rationality in the management of water resources through the allocation of water.

In this approach, the role of water allocation as a management process within the regulation of multiple uses in conflict regions is highlighted. This allocation process seeks to guarantee the common use of the good by users and to establish controlled use, aiming at sustainable development. Still under this focus, Moraes *et al.* (2006) clarify that water scarcity requires policies to be formulated to ensure an efficient inter-sectorial allocation of the resource, while reversing its degradation. Defining an optimal or ideal allocation, through modeling, as a reference for evaluating economic implementation mechanisms that are closest to the optimal value. In this way, appropriate water allocation policy decisions can directly benefit from improved or evolving basin-level water allocation modeling.

In view of this, there is that the optimization of the use of water resources linked to an optimal allocation among users involved in a sectorial dynamic, allows sectorial policies to guarantee water security for the economic development of agents and promote economic rationality for water consumption.

Hydro-economic models are used as an economic mechanism that measures the impact of intersectoral policies and helps decision making for the planning and regulation of water resources. Silva (2017) points out that, such models can measure economic effects of different operational rules, environmental restrictions, and ecosystem services, technical and institutional restrictions. Koch *et al.* (2015) highlights the possibility of these to measure the trade-off between uses, scarcity costs and benefits, as well as shadow prices of institutional and environmental restrictions. Harou *et al.* (2009), argue that hydro-economic models are based on a conceptual platform (Bear *et al.*, 1964; Gisser & Mercado, 1972; Noel *et al.*, 1980) for integrated management of water resources on a regional scale where water is allocated and managed in order to maximize net benefits derived from marginal benefit economic curves.

However, several challenges remain for decision support models for the management of integrated water resources systems. Labadie (2004) and Pulido-Velazquez *et al.* (2006), highlight, as one of the main challenges, the realistic incorporation of hydrological uncertainties. To overcome them, Pulido-Velazquez *et al.* (2013) present a framework for the definition of an allocation mechanism for the use of water based on the marginal opportunity cost, arguing, based on a simulation using a deterministic model for allocating optimum water, that consideration of the marginal value is essential to avoid significant errors in investments and water allocation decisions in the basins. The deterministic scenario is the one adopted in this work, based on the history of water availability during the analysis interval and the possibility of comparing the real solution with the modeled optimization.

The integrated management of water resources, regulated by Law No. 9,433, of January 8, 1997 (Brasil, 1997), reveals its importance in conflict scenarios related to the use of water resources, which according to Amorim *et al.* (2016) are arising not only from water scarcity, but also from the deficiency in the management of these resources. Complementarily Moreira *et al.* (2012) argues that one of the reasons for a water use conflict may be the lack of information that associates water availability with the flows already granted, and this inexistence is directly linked to the lack of planning and management of water resources.

Observations that are in line with what Oliveira & Fioreze (2011) say about water availability need continuous monitoring and studies that account for the current situation and estimate how it will be in the future. Behaviors that bring effectiveness to the granting instrument, instituted in Brasil (1997), for allowing characterizing the behavior of the uses of water in the hydrographic basins, as well as its temporal evolution. Inputs that allow the granting of use comply with its legal role of ensuring quantitative and qualitative control of water uses and the effective exercise of access rights, preserving their multiple uses.

Among the twenty-three hydrographic basins with stretches of federal rivers of special interest for the management of water resources mapped by the Open Data Portal (2020), this work focused on the São Marcos basin, due to the dispute over the use of the resource between the irrigating sector and the electric sector. These uses are not considered priority in a situation of scarcity by the National Water Resources Policy (Brasil, 1997) and therefore require management tools for the regulation and coordination of interests. Among the studies that addressed the São Marcos basin or the hydro-economic modeling linked to conflicts, the works of Jalilov *et al.* (2016), Bof (2018), Machado (2009), Silva & Hora (2005) and Silva (2017) stand out.

Jalilov *et al.* (2016) studied the interconnection and mutual impacts within water–energy–food systems in face of constructing the Rogun Dam through a hydro-economic model referring to the building of Rogun Dam on the Vakhsh River which will provide upstream Tajikistan with hydropower, while downstream countries fear it could negatively impact their irrigated agriculture. The authors examine two potential operation modes of the dam: Energy Mode Irrigation Mode. Neither operation mode provides optimal benefits for all the countries, emphasizing how difficult it is to actually reach a win–win scenario across the water–energy–food security nexus in transboundary river basins.

Bof (2018) aimed to evaluate the economic trade-offs between energy and irrigated agricultural production in the São Marcos basin and show how this information could contribute to the negotiated allocation of water, based on its economic value, comparing with the current allocation system. An explicitly stochastic hydro-economic optimization model was used to determine the economic value of water and its variation in space and time, the results of which were used in a dynamic water accounting. This work concluded that the trade-offs are significant and that there are solutions with the possibility of economic compensation for losses between the sectors involved, solutions that would be the starting point to defuse a conflict situation and signal to users the spatial location and the demand pattern that can be accommodated in the basin, depending on the economic value of the water. In the end, it was proposed that future work should include restrictions for minimum energy guarantees when simulating the operation of hydroelectric reservoirs. The last fact that was included in the modeling proposed in this work, with a view to meeting minimum operating restrictions and the search for hydroelectric generation close to the contractual physical guarantee.

Machado's work (2009) sought to develop a procedure that allows analyzing the issue of water allocation between uses for irrigation and electricity generation, based on economic evaluation methods through the construction of water demand curves applied to the basin of the Preto River. Water in irrigation was valued by the production function method and for hydroelectric generation through the results of simulations of the optimization model used in the planning of the Brazilian electricity sector, NEWAVE, using the mathematical model of the AquaNet flow network for simulations. It was concluded that the economic valuation of water, in addition to being a mechanism provided for in Brazilian legislation, is an indispensable instrument for the effectiveness of water resource management models and should consider the macroeconomic efficiency and conjuncture of the irrigation and energy generation processes, in addition to the type of culture and place of installation of the agents. The author points out that the use of the NEWAVE algorithm for the allocation process implied limitations since it is not possible to evaluate the operation of plants in isolation, reducing the margin for sensitivity analysis around individualized plants. In addition, he stated that it would be desirable in the future to consider any externalities for uses, to make the analysis of the water value resources more robust for economic activities. We tried to remedy these problems in this work by using individualized modeling of the Batalha HPP and the other restrictions adopted by the system's operation. It should be noted that the Rio Preto basin has similar characteristics to the São Marcos basin in terms of the predominance of central pivot, cultures, and climate, being, therefore, a guiding tool for establishing the value of water in the irrigation of the basin under study.

Silva & Hora (2015) aimed in their work to analyze the conflict over the use of water between the current and future demand for irrigation and the hydroelectric use of the Batalha HPP, seeking to evaluate the question of the possible losses of energy produced, associated with the growing consumptive uses at amount of the hydroelectric plant. The mathematical formulation MSUI - Simulation Model for Individualized Plants, developed by Eletrobrás (is a large Brazilian electric power company), was adopted, contributing to the analysis with individualized modeling of hydroelectric plants, as well as through the optics of the maximum flow variable granted, allowing analysis of usage scenarios. The simulation scenarios used the computational tool SisUCA - Plant Simulation System with Water Consumption Uses and obtained energy losses varying between 8.0% and 19.7% for average energy, and between 7.6% and 19.2 % for firm energy. In conclusion, the lack of references to problems solved and well managed in terms of conflicts over the use of water between the electricity sector and agriculture make the São Marcos basin a region of great concern. Noting that, in the medium term, it is necessary to discuss the flexibility of the grants and energy guaranteed by Batalha HPP.

Finally, Silva (2017) aimed to develop and apply a hydro-economic model to determine the optimal allocation of water for the main users in the São Francisco Sub-Medium hydrographic basin. The model uses demand curves generated for consumptive uses, instead of fixed requirements for water resources. The results showed that the rules of operation of the reservoirs and institutional restrictions have a high impact on the costs and benefits of the main economic uses in the study area; and that the institutional restrictions have an impact on the irrigation and energy production sectors, increasing competition between these sectors and between different irrigation projects. Approach of relevant interest for this work, because in the São Marcos basin, in addition to the conflict between the Batalha HPP and the irrigating sector upstream of this, there is also competition between irrigators from the Union, the Federal District and the states of Minas Gerais and Goiás.

3. Methodological strategy

In this work, a model is proposed within the decision support system by means of the computational optimization language that incorporates the water and energy restrictions of the system, such as grants catchment of water and operating limits. The study horizon is from the year 2014 to the year 2019, in which the dynamics of water management between the irrigating sector and the electricity sector are analyzed to meet the grants for multiple uses and power generation at the Batalha HPP. This interval is due to the beginning of the operation of the Batalha HPP in 2014 until the most recent annual data referring to the energy parameters of the enterprise. It is proposed to optimize the allocation of water based on the opportunity cost and the marginal benefit of the agents.

The mathematical modeling for the water allocation optimization problem adopts the deterministic method of solution through non-linear programming. Choice that allows incorporating the nonlinear restrictions present for the electricity sector, such as the fourth order polynomials characteristic of the quota-area-volume curves of each hydroelectric plant, as well as the incorporation of the fall effect for the generation of energy. In such a way that, it is possible to approach the modeling of the real conditions of the conflict and offer analysis of scenarios that discuss management alternatives in comparison with what has been done. However, there are disadvantages for the model, such as the higher application cost and a higher level of complexity due to the richness and scope of the approach adopted, characteristics cited by Corrar (2004) and, also, the incorporation of uncertainties regarding the water affluence in the region and the extrapolation of its probabilities are removed.

The guarantee of optimality of the solution points found is ensured by means of the Karush-Kuhn-Thucker conditions, which, if met, determine that a solution is considered optimal for a non-linear programming problem, as defined in Kuhn & Tucker (1951).

Next, the model proposed in this work is presented, followed by the explanation of the equation regarding the characterization of the electric and irrigating sector, going through the operational and environmental restrictions and the dynamics of uses. It is noteworthy that it is a tool to support the decision to allocate water in a conflict situation, which will be applied to the conflict of Alto São Marcos under its regulatory situation.

3.1. The proposed model

The model developed was based on what was proposed by Fujisawa (2016), for the deterministic optimization of the planning of the medium-term electro energetic operation of hydrothermal systems with isolated plants, and by Silva (2017), for the determination of the optimal water allocation of the main users of the São Francisco Sub-Medium.

The determination of the benefits of users in this model was based on the economic valuation of the quantity of cubic meters of water allocated to each agent. In addition, functions have been incorporated to meet the ecological flow limit and the minimum annual volume allocated to irrigators through grants. Thus, one can indirectly obtain, through comparisons of the restrictions and uses adopted the environmental benefits and costs of the dynamics of economic agents.

To consolidate the formulation base of the model, there is the equation of the objective function as well as the model restrictions presented below.

$$Min \sum_{t=1}^{T} \sum_{i=1}^{I} COirr_i \cdot VzIrr_{i,t} - \sum_{t=1}^{T} \sum_{h}^{H} BmgHidr_{h,t} \cdot q_{h,t} + \sum_{t=1}^{T} \sum_{h}^{H} PLD_{h,t} \cdot (GF - gh_{h,t}) \qquad (3.1)$$

s.t:

$$COirr_i = VAirr_i \cdot J \qquad \forall i \qquad (3.2)$$

$$BmgHidr_h = VAhidr_{h,t} \cdot J \qquad \forall h \qquad (3.3)$$

$$gh_{t,h}(q_{t,h}, v_{t,h}) = k_{esph} \cdot QB(q_{t,h}, v_{t,h}) \cdot q_{t,h} \qquad \forall t,h \qquad (3.4)$$

$$QB(q_{t,h}, v_{t,h}) = NM(v_{t,h}) - NJ(r_{t,h}) \qquad \forall t,h \qquad (3.5)$$

$$NM_t = ko_h + k1_h \cdot v_{t,h} + k2_h \cdot v_{t,h}^2 + k3_h \cdot v_{t,h}^3 + k4_h \cdot v_{t,h}^4 \qquad \forall t,h \qquad (3.6)$$

$$NJ_t = jo_h + j1_h \cdot r_{t,h} + j2_h \cdot r_{t,h}^2 + j3_h \cdot r_{t,h}^3 + j4_h \cdot r_{t,h}^4 \qquad \forall t,h \qquad (3.7)$$

$$v_{t-1,h} + U\left(w_{t,h} - r_{t,h} - \sum_{i=1}^{I} VzIrr_{t,i}\right) = v_{t,h} \qquad \forall t,h \qquad (3.8)$$

$$r_{t,h} = q_{t,h} + s_{t,h} \qquad \forall t,h \qquad (3.9)$$

$$v_h^{min} \leq v_{t,h} \leq v_h^{max} \qquad \forall t,h \qquad (3.10)$$

$$VzEco_{t,h} \leq r_{t,h} \qquad \forall t,h \qquad (3.11)$$

$$s_h^{min} \leq s_{t,h} \leq s_h^{max} \qquad \forall t,h \qquad (3.12)$$

$$q_h^{min} \leq q_{t,h} \leq q_h^{max} \qquad \forall t,i \qquad (3.13)$$

$$VzIrr_{i,t} \leq VzIrr_{i,t}^{max} \qquad \forall t,i \qquad (3.14)$$

$$\sum_{t,i}^{T(a),I} RL_{i,t} \geq \sum_{t}^{T(a)} \left(R_{Irr_{t,i}} - C_{irr_{t,i}}\right) - \sum_{t}^{T(a)} \left(R_{seq_{t,i}} - C_{seq_{t,i}}\right) \qquad \forall t,i \qquad (3.15)$$

$$\sum_{T}^{T(a)} VolIrr_{i,t} \geq \sum_{T}^{T(a)} VolNT_{t,i} \qquad \forall t,i \qquad (3.16)$$

Where:

t	Index of monthly time slots	;	i	Irrigation index
T	Total number of time slots	;	I	Total number of irrigators in the Union domain
h	Hydroelectric plants index	;	a	Year index
min	Index of the minimum limit of the variables	;	max	Index of the maximum limit of the variables
$COirr$	Operation cost of the irrigated sector [R$/m³/s]	;	$BmgHidr$	Marginal benefit of water for the hydroelectric plant [R$/m³/s]
PLD	Liquidation Price Differences [R$/MWh]	;	GF	Physical Guarantee [MW]
gh	Hydraulic production function [MW]	;	QB	Gross drop in the system [m]
VA_{irr}	Economic water value of irrigation water [R$/m³]	;	VA_{hidr}	Economic water value for the electricity sector [R$/m³]
NM	Plant upstream level (fourth order polynomial) [m]	;	NJ	Downstream level of the plant (fourth order polynomial) [m]
$k_{0,1,2,3,4}$	Coefficients of the quota polynomial of the amount level by volume	;	$j_{0,1,2,3,4}$	Coefficients of the downstream level polynomial by defluence
v	Variable of stored volume [hm³]	;		
$VzIrr$	Variable of irrigant flow [m³/s]	;	$VzEco$	Ecological piracema flow variable [m³/s]
w	Variable affluent flow rate [m³/s]	;	r	Variable flow rate [m³/s]
q	Variable of the turbine flow [m³/s]	;	s	Variable flow rate [m³/s]
RL	Variable of net income of irrigant [m³]	;	k_{esp}	Constant of specific productivity of each plant [MW/m³/s/m]
$R_{Irr_{i,t}}$	Irrigation income [R$]	;	$C_{irr_{i,t}}$	Irrigation cost [R$]
$R_{seq_{i,t}}$	Dry income [R$]	;	$C_{seq_{i,t}}$	Dry cost [R$]
$Vol_{i,t}$	Variable volume of water consumed by irrigant [m³]	;	$VolNT_{t,i}$	Volume of water consumed by irrigant see NT 103/2010 - ANA [m³]
U	Constant conversion of the flow in monthly volume in hm³	;	J	Flow conversion constant for monthly volume

It appears that the objective function of the model, set out in 3.1, seeks to minimize the operational cost of scarcity of irrigated perimeters and the difference between the production of energy by the Batalha HPP and its contractually established physical guarantee, while maximizing the economic benefit energy production.

In more detail, considering the multiple uses as restrictions of the model, we have that, for the irrigating sector, the operational cost of scarcity is a variable that impacts optimization. The referred variable, when minimized, is equivalent to the maximization of the net benefit for the sector, respecting the regulatory restrictions, among them institutional, environmental, and operational norms, such as the flow of piracema, in addition to the volume limits granted to irrigators.

The marginal benefit of water to the hydroelectric plant, on the other hand, contributes to the determination of the economic value of the operational policies of the reservoirs and the marginal value of the water stored in them. Approach that reflects the view of Pereira *et al.* (1998), Tilmant *et al.* (2012) and Pereira (1985), that reservoirs are economic agents that offer the service of water transfer over time.

Finally, the third term of the objective function was incorporated to encourage hydroelectric power generation to be the closest to the contractual physical guarantee. In this way, the need to compensate for the energy deficit through the purchase of energy in the short-term market at the value of the Difference Settlement Price (PLD) is reduced.

3.2. Electric sector

The hydroelectric plant directly involved in the conflict in the Alto São Marcos is Batalha HPP, whose exploitation of the hydroelectric potential is held by the concessionaire Furnas Centrais Elétricas SA. The referred enterprise consists of 52.2 MW of installed power, of which 48.8 MW of physical guarantee established by contract. This HPP is located upstream of the other plants in the cascade of the São Marcos River, a federal river that belongs to the Paranaíba basin and contributes to the regularization of hydroelectric projects in the Paraná Hydrographic Region up to the Itaipu HPP. Figure 1 shows the schematic diagram of the hydroelectric plants from the Batalha HPP to the Itaipu HPP, in which it is possible to observe the sequence of uses of the cascade until the flow meets the Atlantic Ocean.

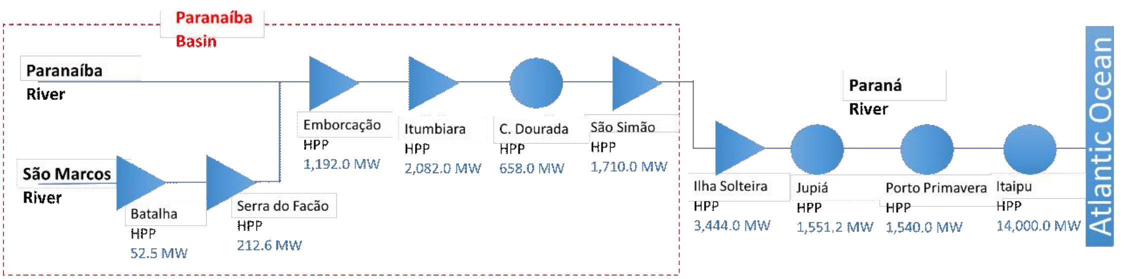


FIGURE 1 – Schematic diagram of hydroelectric plants from the Batalha HPP to the Itaipu HPP.
SOURCE: Data obtained from the schematic diagram of the hydroelectric plants of the SIN (ONS, 2020a). Prepared by the author.

This figure shows the diagram of the water resource utilization structure adopted for the development of the model. In this way, the water in the Batalha HPP is valued based on the consideration that a cubic meter of turbine will run through the downstream plants and potentially produce energy in them.

For the elaboration of the model, it was necessary to survey HPP Batalha's registration data from the NEWAVE deck of January 2020, obtained through the portal of the CCEE (Electric Energy Trading Chamber) (CCEE, 2020), following the example of the reservoir of useful volume, maximum and minimum amount quota, of the fourth degree upstream and downstream polynomials, characteristic of the quota-area-volume curve and the value of specific productivity. These data condition the energy dispatch performed by the National System Operator (ONS), and in the model developed in this work are operational restrictions that interfere in hydroelectric generation together with time, environmental and water availability limitations. These conditions justify the adoption of non-linear programming that incorporates the behavior of energy dispatch in the model.

Additionally, it was verified in the inventory of the hydraulic operational restrictions of the ONS hydroelectric plants (ONS,2016) that the Batalha HPP has as its downstream restrictions the minimum flow of 30.1 m^3 / s, in the piracema period, and 23 m^3/ s, outside the piracema period. This limit was regulated by Resolution No. 489, of August 19, 2008 (ANA, 2008), making it jointly compatible with the operation of the other existing reservoirs. This ecological flow restriction was considered in the equation of the model by equation 3.11 and directly impacts the hydroelectric generation of the Batalha HPP, considering that it imposes a minimum defluent flow.

The value of the water was obtained from the work of Vasconcelos e Silva Júnior (2020), who considers the incorporation of the opportunity cost that the water turbined by the Batalha HPP has on the cascade system downstream of it, as well as the potential for management and regularization of the water resource in relation to the PLD of the submarket in which it is inserted.

The concept of water balance was also incorporated into the model. This consists of a restriction of water conservation in the system, the equation of which is considered in equation 3.8, considering that the multiple uses granted upstream of the Batalha HPP consist of water catchment by the irrigating system. In which the sum of the flows of each irrigant for each instant of time plus the flow deflected by the plant are parameters to be deducted from the flow affluent to it and converted into monthly volume in hm^3 by the constant U. Thus, the value of this accumulated is added to the volume of the previous instant and results in the volume at the current time.

Another very relevant concept for approaching reality is the fall effect. This is understood as the influence of the variation in the fall in the productivity of the hydraulic plant through the variation of the upstream and downstream quotas. According to Read (1982); Soares & Carneiro (1991) apud Fujisawa (2016), with this effect there is an additional cost reduction anticipating thermal generation to postpone hydraulic generation, reducing depletion, and increasing the productivity of hydraulic plants. This concept was incorporated into the model formulation by equation 3.4, in which the product of the specific productivity of the plant by its gross drop (QB), difference between the levels of upstream and downstream of the reservoir obtained by the quota curves -area-volume, and by the turbine flow, results in the value of the hydraulic production of electricenergy.

3.3. Irrigating sector

The focus of the irrigating sector consisted in parameterizing the federal irrigators granted by ANA for Alto São Marcos, located upstream of Batalha HPP and mapped by Technical Note nº 103 / GEREG / SOF – ANA, of August 30, 2010, ANA (2010). The water value for each irrigant was calculated based on the work of Machado (2009) and FGV (2003) and allowed the delimitation of the values of income and cost adopted in the modeling, as well as the dynamics of the annual volume consumed.

By discriminating the demand curve for irrigation in Union rivers in the São Marcos basin, presented in ANA (2010), by the accumulated volume and net income for each of the 59 irrigators, the water value was obtained, in reais per meter cubic[1], effectively distributed in the period of use of the resource. Thus, delimiting the water valuation for the federal irrigating sector upstream of the Batalha HPP under the monthly approach, as shown in Figure 2, in comparison with the monthly water value for the electricity sector obtained by Vasconcelos e Silva Júnior (2020) for the time horizon of the study, from the year 2014 to 2019.

In this figure, the majority of irrigators distribute their irrigation during the twelve months of the year, which inferiorly limits the water value for the sector by approximately 5.8 reais per cubic meter. However, there are still several irrigators that operate only in some months of the year, which are responsible for raising the water value during the period from April to October due to the higher concentration of irrigant and, therefore, greater demand for water. Complementing the analysis, it appears that for the electricity sector the water value has a lower order of magnitude, reaching a maximum of 1.8 reais per cubic meter in February 2014. This value, compared with the high volume of cubic meters of water powered by Batalha HPP in the face of the consumption of irrigators, gains representativeness and becomes a factor that intensifies the dispute between these users. In addition, the seasonality of the sectors allows for a space for negotiating water allocation that shapes decision ranges, aiming, in addition to guaranteeing water and energy security for the system, the incorporation of the economic value of water. Situation that makes the granting of water a relevant planning tool for the two sectors, if well defined.

More recently, the document Survey of agriculture irrigated by central pivots in Brazil (ANA, 2019) highlighted that, for the base year of 2017, the São Marcos pole is characterized by 100,872 hectares of pivot area for irrigation, second place in the national ranking of area and density. This value compared to the one mapped in ANA (2010), of about 8 thousand hectares of irrigated area occupied by federal irrigators in the basin, justified the adoption of the value of ten times the federal irrigators as a reference for the representation of the irrigating sector in the case study. In this way, it was sought to add representativeness in the analyzes and to allow the establishment of a comparison parameter in relation to the values observed over time.

[1] One real (BRL), Brazilian currency was equivalent to eighteen cents of US dollars in March 2021.

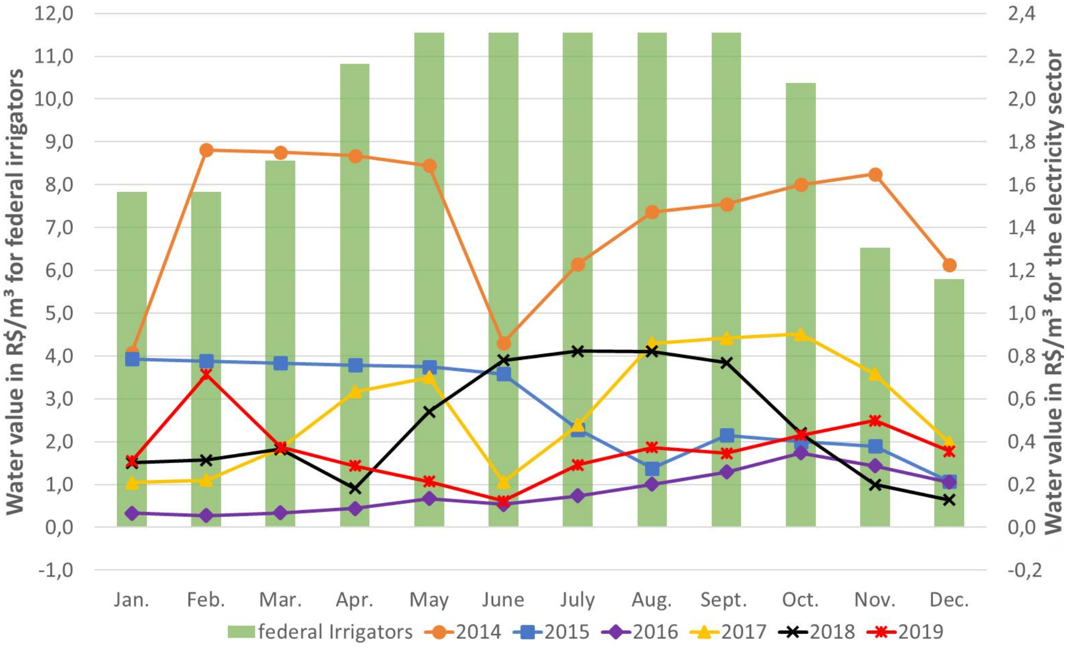


FIGURE 2 – Water value in R $ / m³ for federal irrigators granted by ANA upstream of the Batalha HPP.
SOURCE: Data on ANA grants obtained from Technical Note No. 103 / GEREG / SOF-ANA (ANA, 2010). Prepared by the author.

It should be noted that the impact of probable private reservoirs presents in the region and that could change the water demand for the region were not considered for the modeling of the irrigation sector. An existing externality due to the difficulty of mapping all users for the effective regularization of uses in the basin by Organs managing bodies of the states of Goiás, Minas Gerais and the Union.

In addition, due to the absence of more recently collected data and the high price variability and planting dynamics of agricultural activity in the region, the behavior of the irrigating sector was assumed to be constant during the analysis intervals. It is noteworthy that its values of income and cost were deflated for August 2020, as was done with the PLD data for the electricity sector, which improves the analysis of the parameters of remuneration and water value.

Deliberation nº 60, of March 10, 2016, CBH--Paranaíba (2016a), and Deliberation nº 70, of December 15, 2016, CBH-Paranaíba (2016b) of the Paranaíba River Basin Committee were also considered, which discussed and defined priority for granting the right to use water resources upstream of the Batalha HPP on the São Marcos River for irrigation. This positioning was adopted for the hydro-economic modeling, as presented in equations 3.15 and 3.16, in which the annual grant given to irrigating users was the lower limit of water catchment.

4. Results and discussion

To validate the model and to better understand the results obtained in this work, the results were presented grouped by parameters. Initially, the dynamics between the annual income and the water value per irrigant was presented. Then, the dynamics of income between the electricity sector and the irrigated sector was compared under the real perspective and the results of the modeling. The impact that the allocation had on the economic valuation of water was verified, and, finally, the effect that the optimization and the modeled restrictions resulted in the remuneration of the sectors involved in the São Marcos conflict was evaluated.

4.1. Annual income and water value per irrigant

The dynamics between the annual incomes, in millions of reais, was diagnosed for the irrigating sector upstream of the Batalha HPP, whose reference was ten times the volume of water catchment, and the value of each cubic meter of water consumed during the annual interval. Thus, one can understand the economic efficiency between agents and the impact that each one has on the sector's annual remuneration. Figure 3 shows the referred annual income values and the water value per irrigant.

From this figure, it is observed that the dynamics between the annual income obtained by each irrigant and the value of the respective water tend to be proportional. However, irrigators “i8”, “i13”, “i20”, “i31”, “i32”, “i37”, “i41”, “i44”, “i46”, “i50”, “i51” and “i54”, With emphasis on “i31”, exhibit the opposite behavior, that is, they obtained a high annual income supported by a decrease in the economic value of water. This situation is due to the implication of a high annual volume caught by such irrigators, greater than one million cubic meters per year, indicating that these users have a lower efficiency compared to the others and, therefore, obtain a proportionately lower net income for each cubic meter caught. Result that promotes the discussion of revision of the use licenses combined with levels of efficiency of the water resource caught for this sector. It should be noted that such mapping may indicate the presence of accumulation reservoirs built by users, with a view to reserving a larger quantity of water from a larger intake in certain months of the year.

Another point of analysis is the occurrence of negative water values for the “i37” and “i47” irrigators. Which, according to the calculation and commentary methodology presented in ANA (2010), indicates that for these irrigators it would have been more advantageous to cultivate in rainfed and not irrigate, or else that these are in more favorable topographies, reducing the costs of pumping and justifying their stay in the irrigated sector. In addition, one must consider the question of the dynamics of agricultural activity, which, due to its representative price variation, implies the variation of the crop produced over the years; and it would be a possibility that an economically unfavorable situation may have occurred during the data mapping period.

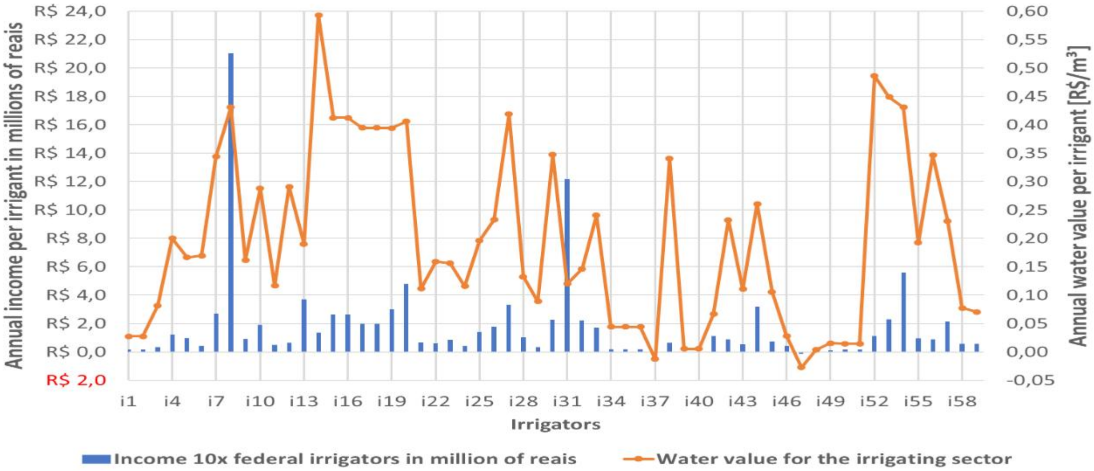


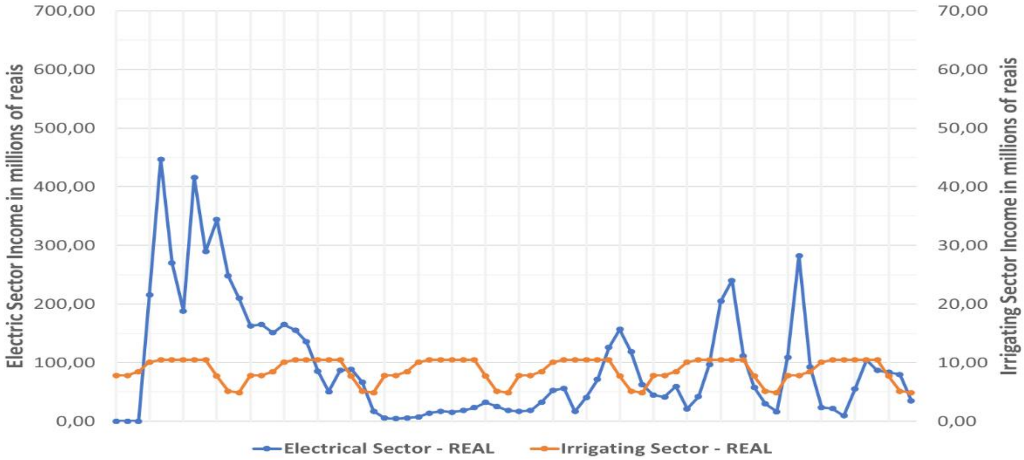
FIGURE 3 – Annual income in millions of reais and water value in R $ / m³ for each federal irrigant granted by ANA upstream of the Batalha HPP. SOURCE: ANA grant data obtained from Technical Note 103 / GEREG / SOF-ANA (ANA, 2010). Prepared by the author.

4.2. Dynamics of uses

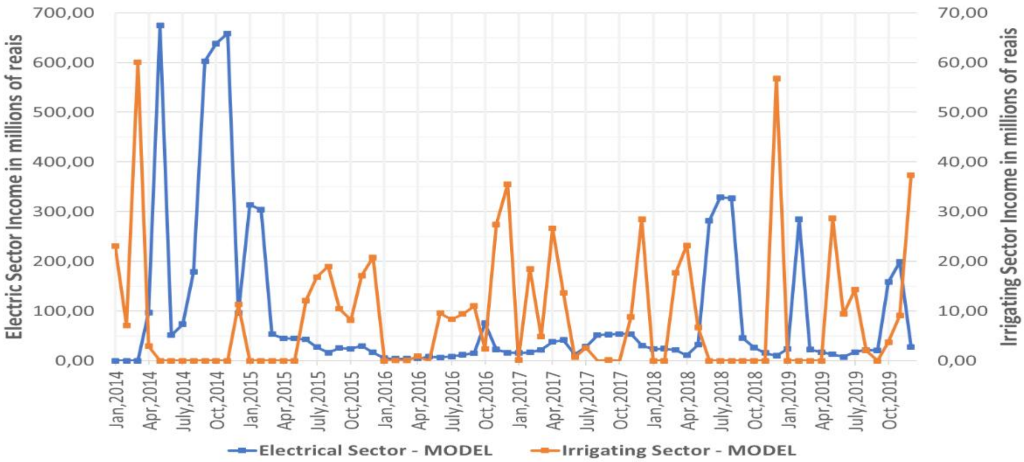
To understand the real dynamics and the model proposed for the irrigating and electric sectors, the income values for each sector were calculated from the equation proposed in this work. Figure 4 presents the results obtained and allows the comparison between the real diagnosis and the optimal modeling of water allocation, based on the monthly income in millions of reais for each sector.

In that figure, letter (a), the real income dynamics between the electricity sector and the irrigating sector in Alto São Marcos was illustrated. It is observed that the dynamics of the irrigators is more standardized, with a higher concentration of income in the period from May to September, this because it was assumed as a hypothesis of the work that this sector would have constant behavior in the analyzed period. In addition, their remuneration range has a smaller variation, which can be explained by the seasonality of the crops during the longest period of the year and, therefore, by the constant volume of water caught. The electric sector, more specifically the Batalha HPP, has a higher income variation, reaching peaks above two hundred million reais and vouchers close to five million reais. This is because, this sector has its remuneration reflected by the behavior of the water valuation for the hydroelectric use of a consolidated market.

When there are coincident periods of higher income between sectors, it is understood that these would be intervals of greater availability to be paid by agents1. Situation that, within the dynamics of demand and supply of the resource, is a point of attention to the subsistence of a water conflict and to the promotion of an optimization for efficiency of the allocation of income. Such correspondence occurred in the months of May/2014, April/2015, June/2016, May/2017, August/2018 and September/2019.



(a) Real dynamics of uses.



(b) Dynamics of uses of the model developed

FIGURE 4 – Annual income in millions of reais for the electricity sector and for the irrigation sector based on the dynamics of real behavior and the model developed at work.

SOURCE: Actual data: Technical Note 103 / GEREG / SOF-ANA (ANA, 2010) and ONS website (ONS, 2020b). Prepared by the author.

In that figure, letter (b), the result was obtained by minimizing the operational cost of scarcity and by maximizing the economic benefit of energy production. The response of the model proposes time intervals with null values of remuneration by the irrigating sector and with greater variation. This behavior allowed the implication of higher income peaks for both sectors, a dynamic that is possible if there is a negotiation between the volume of water caught by irrigators and the volume of accumulation by the hydroelectric reservoir.

It is worth mentioning the year 2014, when the irrigated sector intensified its consumption in March, before the start of operation of the Batalha

HPP, and, in December, also, allowed the hydroelectric plant to take advantage of the influx of the basin in the months of May to November. Contrary to what happened in 2015, when the irrigation sector started canceling its water consumption until the month of May, a period in which it was allowed to obtain the highest income for the electricity sector. Subsequently, irrigators obtained an increasingly higher income, even surpassing the income of the electricity sector in the month of August. 2016 was a critical year in terms of income for the electricity sector, especially in the months of June, November and December, when there was the greater water catchment by irrigators, in addition to the restriction on the granting of grants defined in the model. Finally, in 2018 the highlight was the peak remuneration of 56 million reais in December for the irrigating sector. This value was made possible by the complementary dynamics to the electric sector, which obtained its highest remuneration from June to August, when water catchment was null for irrigators.

4.3. Water value

When addressing the variation in the water value (WV) for the irrigating and electric sectors, it was opportune to observe the economic rationality in the valuation of the resource for the periods of analysis, since the WV implies, together with the volume of water caught, in the remuneration of agents. Figure 5 presents comparatively the behavior of the WV for the irrigating sector in the real dynamics and proposed by the model, in addition to allowing the comparison with the WV of the electric sector for the Batalha HPP in the same period.

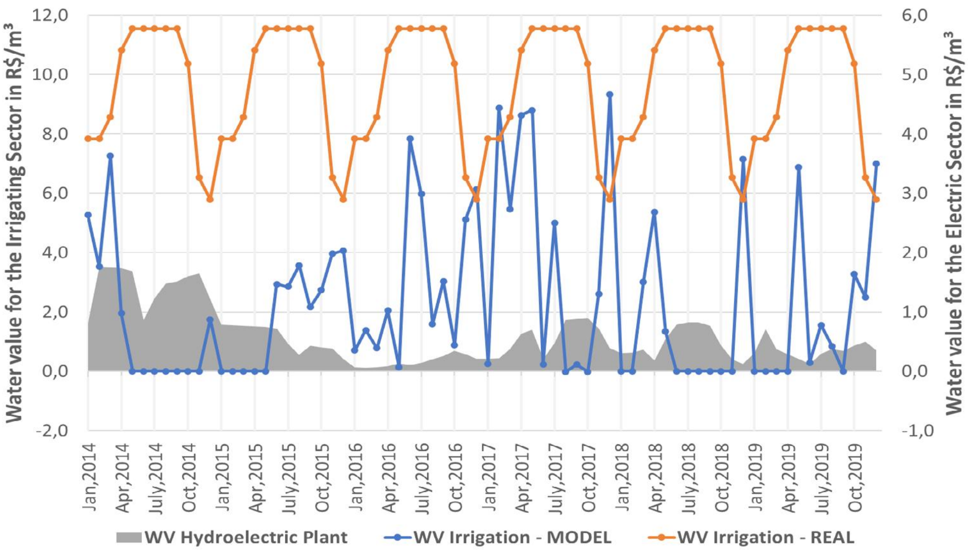


FIGURE 5 – Water value for the irrigating sector based on the dynamics of the model elaborated at work and the real dynamics in comparison with the water value for the hydroelectric plant, for the year 2014 and 2019.

SOURCE: Data on irrigators obtained from Technical Note 103 / GEREG / SOF-ANA (ANA, 2010) and data from Batalha HPP obtained from the ONS portal (ONS, 2020b). Prepared by the author.

This figure allows a better comparison between the WV for the irrigating sector compared to the real dynamics and the model proposed in contrast with the WV for the electric sector from the perspective of the Batalha HPP. It is observed that the time intervals in which the increase in the water value coincided with the irrigated sector in relation to the electric sector were minimized from the result of the model.

In addition, it is known that the water value for irrigation of the model was lower than the real one, because there was an optimum economic allocation. In other words, a better allocation allowed the water value to be lower, with greater economic rationality and less dispute between resources.

Moments of zero water value for irrigators indicate an incentive to zero consumption for the period, allowing the hydroelectric plant to take advantage of the peaks of water valuation in its sector. An application of such behavior would be the use of compensation measures, which would allow one sector to grant its right of use so that another could, in the same period, effect its consumption with less competition. The peaks in the water value of the irrigating sector, on the other hand, indicate a different temporal distribution of uses and a model response to the dynamics established between the electricity sector and even among irrigators. This is because, unlike the actual irrigating VA, the model distributed within the limits of each of the irrigators its volumes caught and consequent remuneration in shorter time intervals, however, allocated in favorable periods of supply of the resource. Such dynamics made it possible that, economically, the model irrigating WV is smaller than the real irrigating WV, respecting the various restrictions considered.

In addition, attention should be paid to the inflection points between water valuation trends, as occurred in May 2018. This intersection indicates a balance point between the uses for the valuation curves, that is, a point optimal allocation. What is economically supported by the principle of microeconomic equimarginality, explained by Moraes (2012), as the one that establishes that in an optimum allocation between sectors, each sector derives the same utility from the last unit of the allocated resource. It should be noted that Harou *et al.* (2009) states that, even in modeling, the principle of equimarginality is not always met, neither spatially or temporally in the network, given the incorporation of non-economic restrictions, such as hydrological and institutional ones; as is also the case with the modeling adopted at work.

4.4. Income comparison

Finally, the impact on the income of the sectors was analyzed annually, to measure the effect that the ecological restrictions and the deliberations of the committee for the prioritization of the irrigating sector have for each remuneration. Figure 6 shows the referred comparison between annual rents, in millions of reais, for the electric sector and for the irrigated sector, based on the dynamics of the model elaborated in this work in comparison with the real dynamics consolidated through ANA data (2010) and ONS (2020b).

This figure allows comparing the model's response to the real dynamics of annual income for each sector. It can be observed that the restriction on meeting the annual income by the irrigating sector was accepted in all years of the study by the lower limit. It should be noted that the income could be higher if there was water availability and the other restrictions were met, in view of being an operation that seeks to minimize the cost of scarcity.

As for the income of the electric sector, it is observed that only the years 2014 and 2018 obtained a higher remuneration for the model than the real one. 2014 was the year in which the Batalha HPP began to operate, which allowed irrigators to collect more in the initial months, without rivalry of uses, and for the hydroelectric plant to take advantage of the affluence regime with less water competition. The year 2018 had a higher remuneration for the electricity sector because the water value was favorable for it and the irrigators met their demand in complementary time intervals.

The year 2017 stood out due to the lower hydroelectric generation compared to the real one, approximately 50% of that achieved. This value indicates that the cost of priority service for irrigating users was the lowest generation at Batalha HPP, and therefore had a financial impact on the sector. In addition, the years 2015 and 2019 also showed lower earnings in the electricity sector, with respectively 54% and 71% of the consolidated real total.

Such diagnoses are pertinent to measure the impact of hydrological and institutional restrictions when adopting a regime of prioritization of uses and discussing policies for reallocation and regularization of consumed flows, within a scenario of water scarcity established in a water system, as in the case of Alto São Marcos.

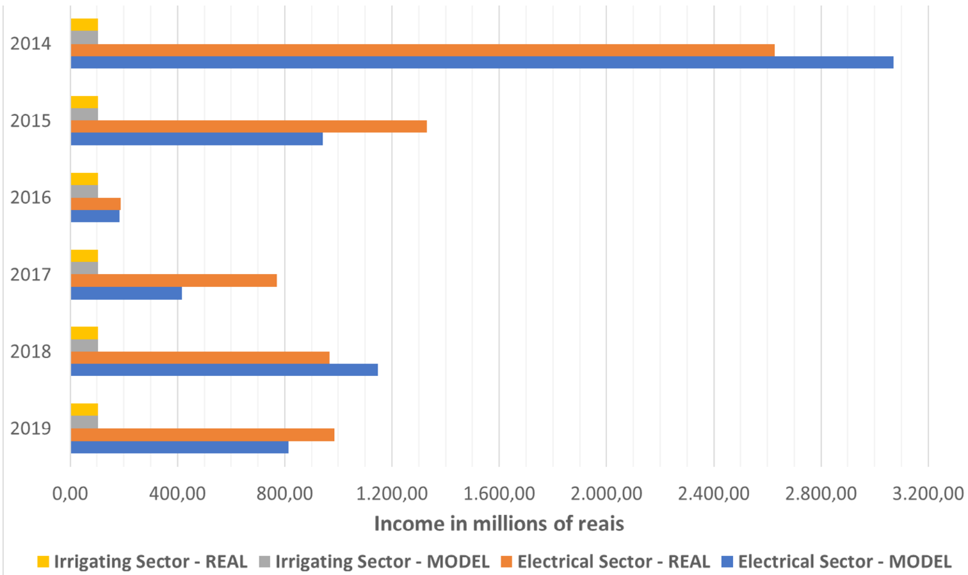


FIGURE 6 – Comparison between annual rents in millions of reais for the electricity sector and for the irrigated sector based on the dynamics of the model developed.

SOURCE: Elaborated by the author.

5. Policy conclusions

This work proposed and applied hydro-economic modeling as an economic instrument for the allocation of water in the conflict of the Alto São Marcos. From its results, it was verified the efficient compatibility of the multiple uses of the water resource. The proposed dynamics added economic rationality in the scenario of prioritizing the use of water to meet the annual irrigation demand of water catchment and their respective incomes, in view of the proposal to maximize the marginal benefit of hydroelectric power generation at the Batalha HPP.

The impact that hydrological and institutional restrictions have on the agents was measured from the comparison with the real dynamics, as well as points of inadequate utilization were highlighted, and allocation improvements were proposed. The optimization pointed to lower water values for the irrigating sector, as is expected from a model that minimizes the cost of scarcity and that efficiently allocates water resources. This result indicates the efficiency of the configured seasonal dynamics and promotes support for the discussion of the policy for prioritizing uses and reallocation of the resource.

An important limitation of this work must be highlighted. The absence of updated data from irrigators from Goiás, Minas Gerais and the Federal Government in relation to the flows granted, income and cost, as well as the absence of current data on the effective regularization in relation to the management bodies, which implies not considering the impact of private reservoirs in the region, and the absence of recent data on the dynamics of prices in the irrigation sector. The way found to circumvent such limitation was to parameterize these users in view of the percentage of federal irrigators mapped in 2010. Thus, the analysis based on the amount of ten times the number of federal irrigators allowed to add representativeness to the sector, fostering discussions about the impact of the consumptive uses upstream of the Batalha HPP and to establish a reference for irrigating agents in Goiás, Minas Gerais, Federal District, and the Federal Government regarding the limits of water supply.

It should be noted that the choice for a deterministic approach in hydro-economic modeling did not incorporate the uncertainties related to water inflow in the region and the extrapolation of its probabilities. It is also noteworthy that the incorporation of restrictions that, together with non-linear programming, allowed the modeling of the real conditions of the conflict to be brought closer and offer analysis of scenarios that discuss management alternatives in comparison with what was carried out.

The results of a hydro-economic model can be understood as a starting point for the modeling platform from which refinements are added. It is suggested, for the continuation of this research, the discrimination of the irrigating sector among the dominialities that rival the use in the basin, the insertion of annual growth values of the irrigating sector and users downstream of the hydroelectric exploitation of Batalha HPP, in order to characterize for a larger panorama the dichotomy between uses.

With a focus on the electricity sector, it is recommended to analyze the impact of the change in the physical guarantee, the insertion of minimum generation service restrictions and the analysis of various values of multi-use grants upstream of the Batalha HPP, to establish prospective plug scenarios decision-making.

The proposed improvements aim to make the conflict dynamics modeled in Alto São Marcos more robust and to support the decision making of stakeholders in the basin regarding the management of the resource and its economic choices. In this way, it seeks to promote greater water and energy security to the dynamics of current and future uses, and greater efficiency to the intersectoral and normative plans applied to the conflict.

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