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A Water Allocation Model for Multiple Uses Based on a Proposed Hydro-Economic Method

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Abstract: Water scarcity drives society to conflict over the allocation of water. Economical externalities based on the development of water production improve the decision-making process for planning water allocation and the operation of the water infrastructure. We present a proposed water allocation model using a priority-based and hydro-economic optimization kernel as a framework for improving the quality of information for the different user sectors, stakeholders, and institutions for the water allocation decision-making process. In addition, we propose a method for using hydro-economic optimization models without the marginal benefit curve of water demand. The proposed model, called AcquaNetGIS, was applied to the São Francisco Transboundary System, and the hydro-economic optimization was improved, allocating 7.0% more water for all users considered, including water supply, irrigation, and hydropower. Moreover, the minimum flow downstream from the Xingó hydropower station reached 98.5% (priority-based optimization) and 99.0% (hydro-economic optimization) during the optimization period. Depending on the rules and legislation, the sustainability of water allocation based on hydro-economic externalities may be a better solution for the planning and operation of complex water infrastructure systems. Multicriteria decision-making methods should consider the results of the proposed model in order to understand the stochastics of the hydrological regimes and economic production based on the availability of water.

Keywords: water conflict resolution; water security; decision-making; water management; São Francisco transboundary

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Citation: Vichete, W.D.; Méllo Júnior, A.V.; Soares, G.A.d.S. A Water Allocation Model for Multiple Uses Based on a Proposed Hydro-Economic Method. *Water* **2023**, *15*, 1170. https://doi.org/10.3390/w15061170

Academic Editors: Yejun Xu, Carlos Llopis-Albert and Stefano Alvisi

Received: 21 December 2022
Revised: 24 February 2023
Accepted: 9 March 2023
Published: 17 March 2023

1. Introduction

Water conflict has been a problem with physical, quality, social, political, and environmental aspects, usually caused by the scarcity of water [1–4]. The decision-making process regarding the allocation of water to minimize conflict and achieve sustainability has been a challenge [3,5,6]. The competition for the resources of water, energy, and food is still ongoing [7]. According to [8], we are facing a lack of a successful nexus approach to solve the practical problems of water allocation conflicts. Although global institutions and organizations have called to promote the nexus agenda, significant barriers to progress persist, such as cross-disciplinary collaboration, the interdependency of the political economy, complexity, and the objectives of institutional structures [8–10]. From an engineering point of view, mathematical algorithms for simulation and optimization have been used as a decision support system to understand the water allocation systems [11–13]. According to [12,14–18], the optimization option has proven to be an important framework for the decision-making process and finding a trade-off among the water users and stakeholders. The optimization models for water allocation usually rely on a minimum or maximum network cost flow, using priorities to deliver water based on regulations, legislation (priority-based models), or economic values (hydro-economic models). Economical externalities based on water allocation provide valuable additional information for the decision-making process and stakeholders [19–21].

A review of the hydro-economical water allocation models (HEWAM) was carried out by [20,21]. The output and their application were still not applicable to planning and the operational rules of water infrastructure, as concluded by [21]. A participative and collaborative decision-making process should be considered to mitigate the application of HEWAMs [20]. These models were applied successfully by [22–29]. Hydro-economic optimization relies on the marginal benefit curves of water demand according to the characteristic of the user sector (irrigation, urban supply, hydropower, ground water, and the environment). Econometric analysis was used to construct the water demand curves. In general, the water demand curves show the variations in water consumption based on the price variation (price elasticity). The price structure, policy, and climate have different price elasticity responses [30–33]. The users' consumption response in a water demand curve is uncertain [32]. In addition, a quantitative and qualitative database of prices and consumption is required for different water users [19,21,34].

In this article, we present an evaluation of the results of optimizing water allocation via a priority-based and hydro-economic optimization network flow. The water available for each user sector (mean discharge provided), the sustainability index, and the flow duration curve were selected to analyze the model's results. The authors of [28,35] have shown that the hydro-economic model has better water allocation options for urban supply.

As a result of the scarcity of data and information on water users from developing countries, we present a water allocation model based on priority-based and hydro-economic optimization (AcquaNetGIS). In addition, an alternative method of using hydro-economic optimization according to the economic pressure of the user sectors is included in the application of the model. The proposed method to be used for the hydro-economic models creates a link between water availability and economic values based on production for each user sector (irrigation, urban supply, and hydropower energy generation). We are aware that the non-linearities of irrigation water and crop yield [36], the minimization of energy generation by a hydropower station's water head caused by the downstream rating curve, and multiple sources of urban supply could result in a different solution. The proposed model (AcquaNetGIS) and method of hydro-economic optimization highlighted the pressure of economic production on the allocation of water and provided valuable results for understanding the economic externalities that should be considered in the decision-making process for planning and operating the water infrastructure or included in a multicriteria decision-making process for planning the allocation of water. Although sustainability includes different dimensions, we considered the sustainability of the water allocation decision-making process based on the economic pressure for water urban supply, irrigation, and hydropower that is achieved when a solution provides more water for the user sectors to minimize the economic losses.

The proposed AcquaNetGIS was applied to the São Francisco Transboundary System (SFTS), one of the biggest transboundary systems in the world, with a pumping capacity of 126 $m^3 \cdot s^{-1}$. The economic pressure curve, based on the production of goods and services linked to the water flow demand for each user sector, showed an important trade-off between the water used for irrigation in the São Francisco Basin upstream from the Sobradinho hydropower station and for irrigation in the North Line of the SFTS. With the SFTS on, the turbine flow of the downstream hydropower stations decreased by 2.0% (Luiz Gonzaga, Paulo Afonso System, and Xingó stations). Both optimization options in the model application reached 98.5% (priority-based) and 99.0% (hydro-economic) of the minimum flow legislated for the network's outflow (800 $m^3 \cdot s^{-1}$). In summary, the hydro-economic optimization increased the volume of water allocated by 7.0% for all of the considered users. The model's application was constructed on the basis of the flow recorded between January 1941 and June 2021.

AcquaNetGIS produced valuable results of hydro-economic optimization based on the economic pressure of water demand. As presented by [19–21], hydro-economic optimization is a powerful method that must be used for planning and operating the water infrastructure and for allocating water. The proposed method was used to construct the production curves, based on water availability, to improve the gap between the model's results and their application. The Section 2 presents the model framework, the kernel of the optimization model, the proposed method for the hydro-economic models. and the application of the model to the SFTS. In the Section 3, we present the application of the model to the SFTS according to the results of the mean flow provided to each user sector, the flow duration curve, and the percentage of total required flow. The subsequent section presents a discussion about the results of applying the model for resolving the conflict among the user sectors, the operation of the Sobradinho reservoir, the sustainability index, and the minimum flow at the network's outflow. The last section presents the conclusions of the study and the application of the model.

2. Materials and Methods

Optimization models have been used for allocating water and resolving conflict in regions of water scarcity [2,3,21,37]. The author of [20] found that 300 hydro-economic models have been developed, with 25 focusing on watershed transposition. These models have been used for planning, operation, and assessment analyses. In general, optimization models have the objective function of achieving sustainability for the users' water demands [11,13,38]. These models can be based on service priorities (priority-based) or economic parameters (hydro-economic). In a scenario with multiple users, the decision-making process for the planning and operation of water allocation is a challenge [5,6,37]. Knowing the economic, environmental, and socio-cultural externalities induces factors that can be crucial in the context of managing multiple water users and water security for food, urban supply, and generating electric energy by hydropower [5,39].

We propose a water allocation model based on hydro-economic optimization (AcquaNetGIS). Alternatively, the model can also be used as a priority-based optimization model. This is possible through an optimization of the network flow that considers an objective function, where the cost to be minimized can be a user or service priority, or an economic benefit/deficit. The AcquaNetGIS optimization kernel used the Pywr library [40] to minimize the network's flow cost. The proposed water allocation model and the application of the model to the São Francisco Transboundary System in Brazil was conducted according the data from [41–43]. The AcquaNetGIS of the SFTS is fully available [44].

2.1. Model Overview

The AcquaNetGIS water allocation model aims to enable the consideration of economic parameters based on production due to water availability in the optimization of the water allocation models for the decision-making process. The hydrological seasonality, the planning and operation of the water infrastructure (reservoirs, channels, transpositions, etc.), the institutional policy, the economic production linked to the use of water, and the stakeholders are the main information used as the input data of the proposed model. AcquaNetGIS used the Pywr library [40] for the optimization of the network flow. This library allows the cost in the network flow to be the priority or an economic value of a benefit or loss.

The construction of the network flow consisted of creating the topology of a water resource system by relating the inputs and outputs of water, which represent the water infrastructure. Structures such as reservoirs, turbines, transpositions, channels, water intakes, etc. are represented by nodes. These nodes have characteristics that depend on what they represent, such as reservoirs, water extraction, or a water input into the system, among others. Figure 1 illustrates the construction of the topology for the optimization model.

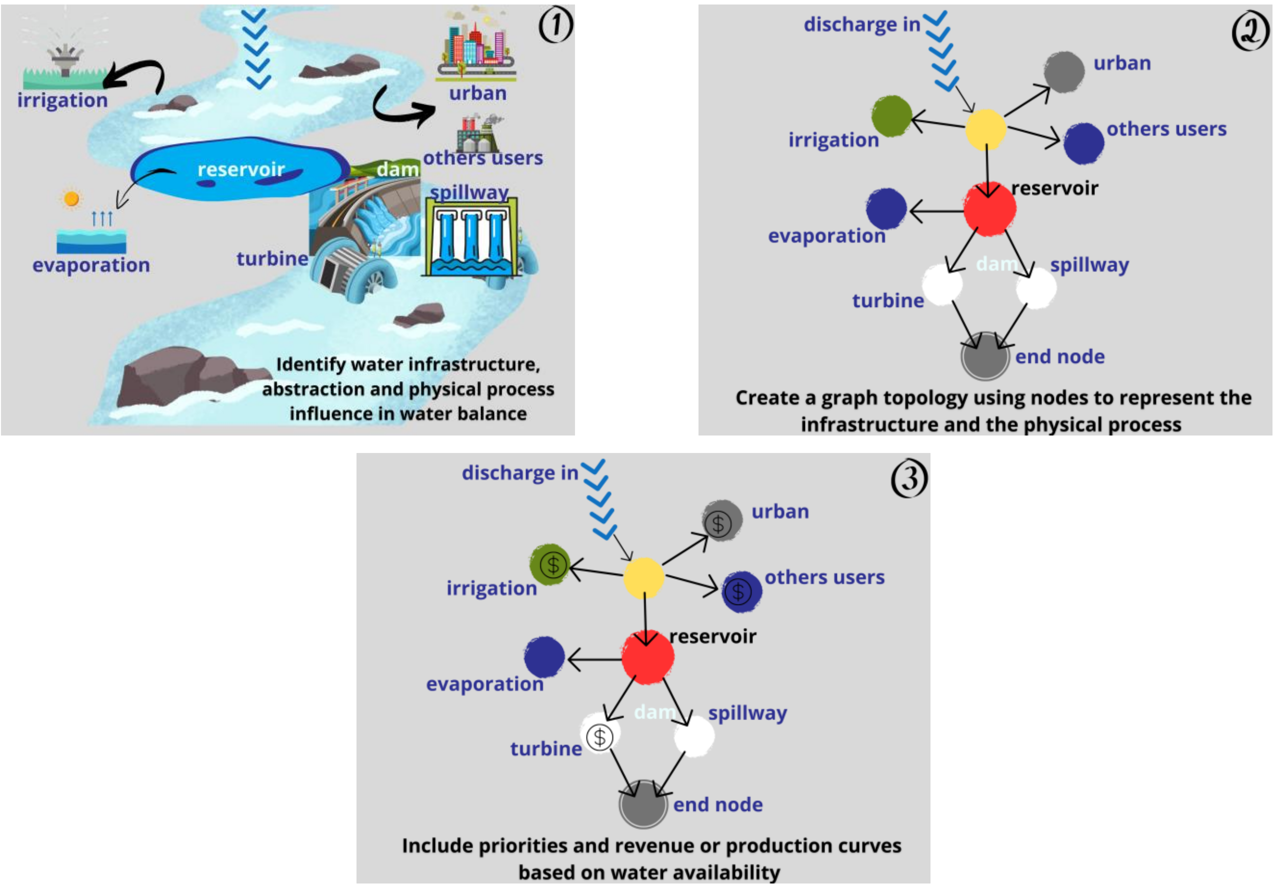

Figure 1. Topological representation of the water infrastructure in a river system as a graph. Figure step 1 represents the process of identifying water infrastructure, abstraction, and physical processes that influence water balance. (**Step 2**) represents the creation of a graph topology using nodes to represent the elements identified in (**Step 1**). (**Step 3**) includes priorities and revenue, or production curves based on water availability.

The Pywr library [40] allows the use of multiple mathematical optimization algorithms. However, the library provides standard linear programming (LP) to determine the allocation of water in the network for each time step, based on [45,46]. The LP method has often been used to address water allocation problems [47]. The objective function consists of:

$$minimize \sum C' \cdot Q \tag{1}$$

$$subject\ to:$$
$$a \leq Ax \leq b,$$
$$l \leq Q \leq u$$

where C is the cost or penalty in a priority-based or hydro-economic optimization, Q is the discharge (flow) for each time-step, Ax is the volume A for storage node x, a and b are the lower and upper limits of the storage volume, and l and u are the lower and upper limits of a node. All of the data are given as volume per day.

The entire formulation of the optimization is presented in the appendix section of [40]. A discussion about the use of linear programming and optimization algorithms has been provided by [11,40,48,49]. We are aware of the use of dynamic programming (DP) in water allocation optimization models and the differences used to solve the optimization problems [18,47,50,51]. However, here, we focused on the differences between the results of the optimization achieved by the proposed model using the priority-based and hydro-economic approach to determine the optimal water allocation solution. In addition, we proposed an alternative to the water demand curves for the hydro-economic models.

The AcquaNetGIS consists of building and configuring a network flow using the priorities and economic benefits/losses. The results are further analyzed in the context of hydrological indicators, sustainability indicators, economic indicators, and the indicators of hydrological changes. The scenarios considered that the operational rules, institutional conditions, and planning for sustainable water use in a collaborative and participatory decision-making process [5] would have information on the externalities and trade-offs between multiple water users for a better water allocation solution. Figure 2 present the model's proposed scheme.

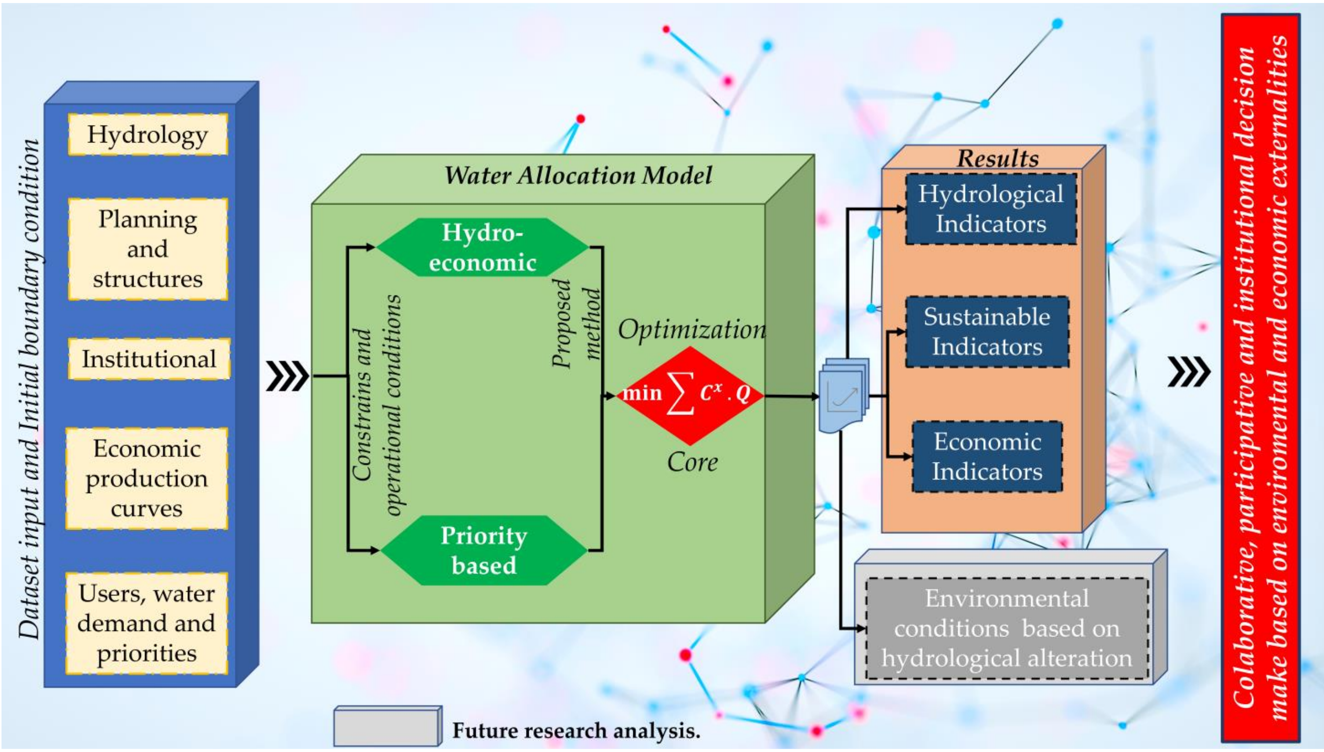

Figure 2. The proposed AcquaNetGIS water allocation model.

The setup of priority-based optimization uses a user-supplied cost that seeks to represent the order of delivery for the water demanded in a network flow. This priority usually seeks to represent the criteria established by laws, guidelines, or negotiated decisions regarding the allocation of water. For instance, in Brazil, urban water supply and water for animals are given higher priority than other water demands and uses.

Hydro-economic water allocation models usually rely on marginal benefit curves (or water demand curves), which depend on the characteristics of the water users. A water demand curve has a function that explains water consumption as a marginal price based on the parameters that influence the consumption, particularly within the water urban supply [34]. The marginal prices included the cost of production for making or producing one additional unit (or delivering more water). The relationship between a change in the water price and the consumption is the price elasticity. The price elasticity plays an important role in a water demand curve, meaning that the range of consumption is according to the range of the price per unit. An elastic demand represents an equal range of consumption and price, and an inelastic demand represents differences in the variations in the range of the consumption and price (Figure 3). The price elasticity of water is a function based on the neoclassical economic theory [52].

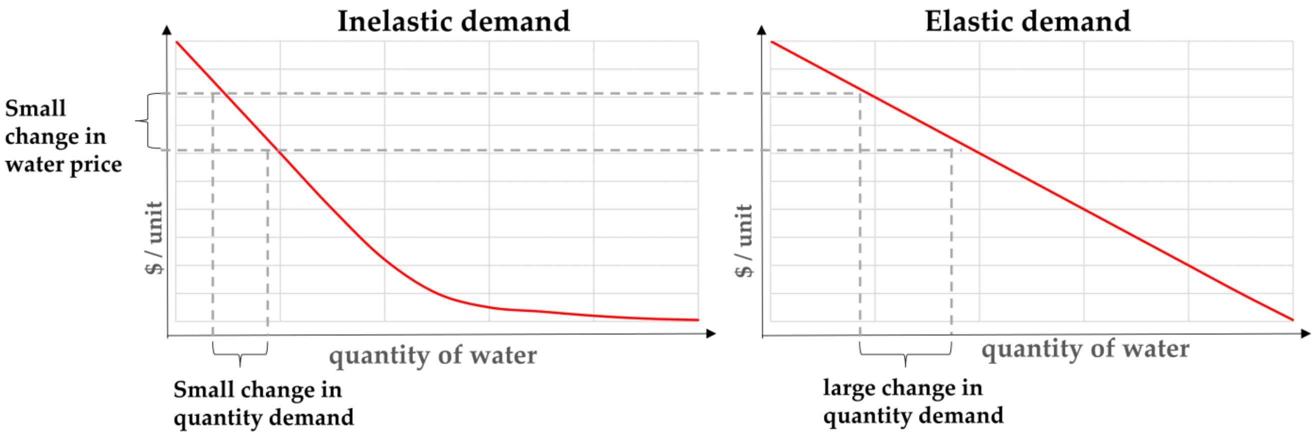

Figure 3. Elasticity of the price and consumption of water (adapted from [30]).

The use of hydro-economic optimization is based on the construction of marginal benefit curves. Depending on the characteristics of the user sector, the variation in the water price has a minimal influence on the consumption of water, e.g., for hydropower generation and irrigation. As an alternative to marginal benefit curves, we propose to use curves of avoided losses based on the revenue obtained by each user sector, linked to the production function of the water use. The authors of [28] used this method in a hydro-economic water allocation model for urban supply to the Cantareira System (Brazil).

2.2. Method Overview

Hydro-economic models for optimizing water allocation seek to represent the economic value of water scarcity [21]. These models have been used in the planning and management of water resources, and to develop new public policies for the operation of the water infrastructure [19,19,25]. Hydro-economic allocation models are commonly used to support decisions [22,24,26,28,37,53]; these models are also used in regions where economic development is dependent on the management of water allocation. The use of this type of allocation model is based on the use of water demand curves to establish the costs in the optimization of the network flow. The use of water demand curves in hydro-economic models reflects the variations in water consumption as a function of the variations in the price of water, which is referred to as price elasticity. The users' response is uncertain and depends on climatic, socio-cultural, and economic characteristics [31,34,54]. It should be kept in mind that the use of price to leverage the conservation of water should be used with caution, as the demand response is not always certain [32].

Considering the lack of infrastructure in developing countries and analyses based on an engineering approach, sustainable planning for water security should have a tangible economical dimension regarding the socio-environmental intangibles of delivering water and promoting improvements in sanitation. However, in engineering a viable water infrastructure and planning for water security under integrated water management, achieving sustainability could have an economic dimension regarding the social and environmental aspects [55–57].

Usually, marginal water demand curves are based on the econometric data that evaluate the sensitivity of the water consumption to price variations, including climatic, economic, and social factors [33,34,38,58,59]. However, using a linear programming optimization method will require the use of the piecewise technique [60]. In other words, this technique consists of partitioning the non-linear water demand curve into small pieces. The Pywr library allows the piecewise node to include the minimum and maximum flow constraints based on the cost for each segment of the water demand function (Figure 4). This implementation was previous applied by [61]. In other words, the piecewise link node has multiple links with different flow and cost values in parallel, according to [40].

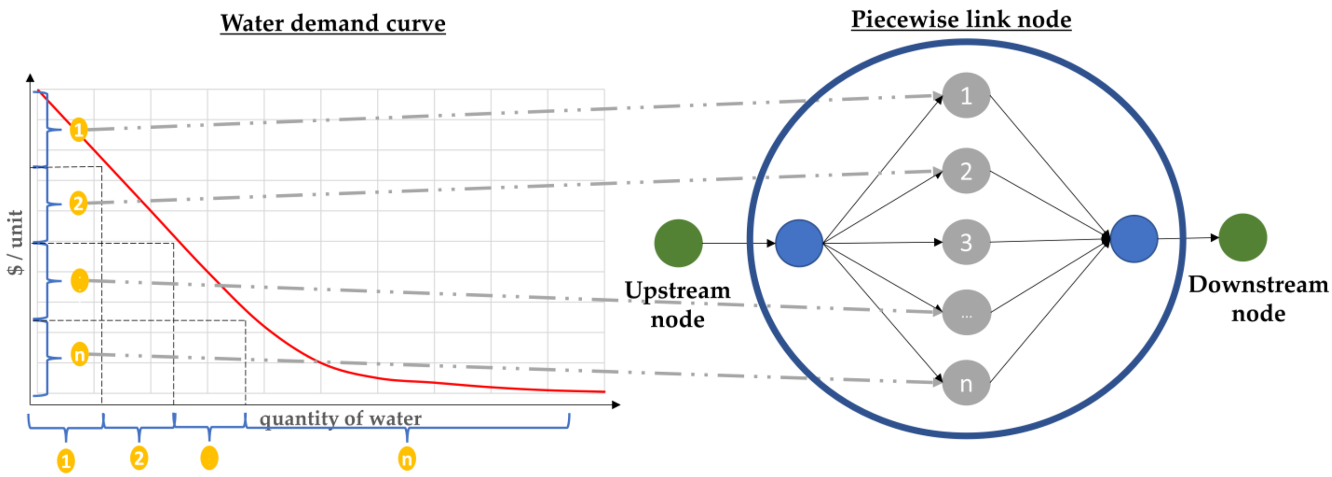

Figure 4. Representation of the hydro-economic node based on piecewise linearization (adapted from [40]).

The proposed methodology of the avoided water scarcity benefit curve includes the economic link to production based on water availability, which relies on the existent or planned user sectors, the existent water price, and the existent or planned water infrastructure. The benefit of delivering a certain amount of water is considered to be equal to the economic loss avoided in a water production system, as presented by Equation (2):

$$B_{Qi} = (Q_t - Q_i) \times [(P_m - P_o) \cdot V_t] \tag{2}$$

where B_{Qi} is the loss avoided when the flow Q_i is made available ($), Q_t is the total flow demanded (m^3/s), Q_i is the flow made available, P_m is the average tariff price ($\$/m^3$), P_o is the average operational cost ($\$/m^3$) that considers the supply of Q_t, and V_t is the total volume in the selected analysis period (usually the monthly scale).

The inclusion of economic externalities can also be considered by the economic pressure of each user sector's demand for water and its production. Therefore, the flow demanded by a user sector is directly related to its revenue. This relationship is not always linear. For instance, some crops have yield reductions that are not proportional to water deficits [36]. On the other hand, energy generation can support periods of water scarcity by regularizing flows in reservoirs, thus maintaining a more stable potential energy, even with variations in the reservoir's inflow. The urban water supply can also use reservoirs for regularizing the variability of flows to improve the ability to supply the flows demanded. The pricing structure of the water tariff can induce non-linear relationships among production, the operational costs, and the revenue generated by the water function. Equations (3) and (4) provide the costs based on the user sector's revenue linked to the production values of goods and services:

$$C_j = f(Q, R,) \tag{3}$$

$$C_j = -1 \cdot \left(\frac{1}{n} \cdot Q_m * \frac{1}{n} R_t \right) \tag{4}$$

where n is the fraction of the maximum flow rate required, Q_m is the maximum flow rate required, and R_t is the revenue generated by the maximum flow rate supplied. The cost should be established according to the model's calculation time-step. This means that the revenue should be monthly for a monthly calculation time-step.

This proposed method simplifies the process of obtaining an input dataset for hydro-economic models by using structured and systematized criteria. This means that the results can provide a perspective of the demands that do not require alternative water sources, providing a better economic benefit for the system being analyzed.

The use of the proposed methodology has different implications for the different sectors considered in integrated water resource management. The urban water supply must guarantee a high percentage for urban supply, whereas irrigation can accept deficits in periods when the crop does not need water. On the other hand, hydropower is based on the analysis of the hydrological variability for defining its installed capacity. Additionally, the generation of hydroelectric energy can consider regularizing the flows to guarantee the ability to supply the necessary flows for the turbines.

The proposed methodology uses the avoided cost of water scarcity based on the existing or planned infrastructure. The water consumed by the users was tested by using the water allocation algorithms of Pywr [40]. We applied the proposed method and AcquaNetGIS to the São Francisco Transboundary System. Figure 5 presents the locations of the water infrastructure considered in the application of the methodology. The Supplementary Material provides complementary information regarding the characteristics of the SFTS, the users, and the hydropower.

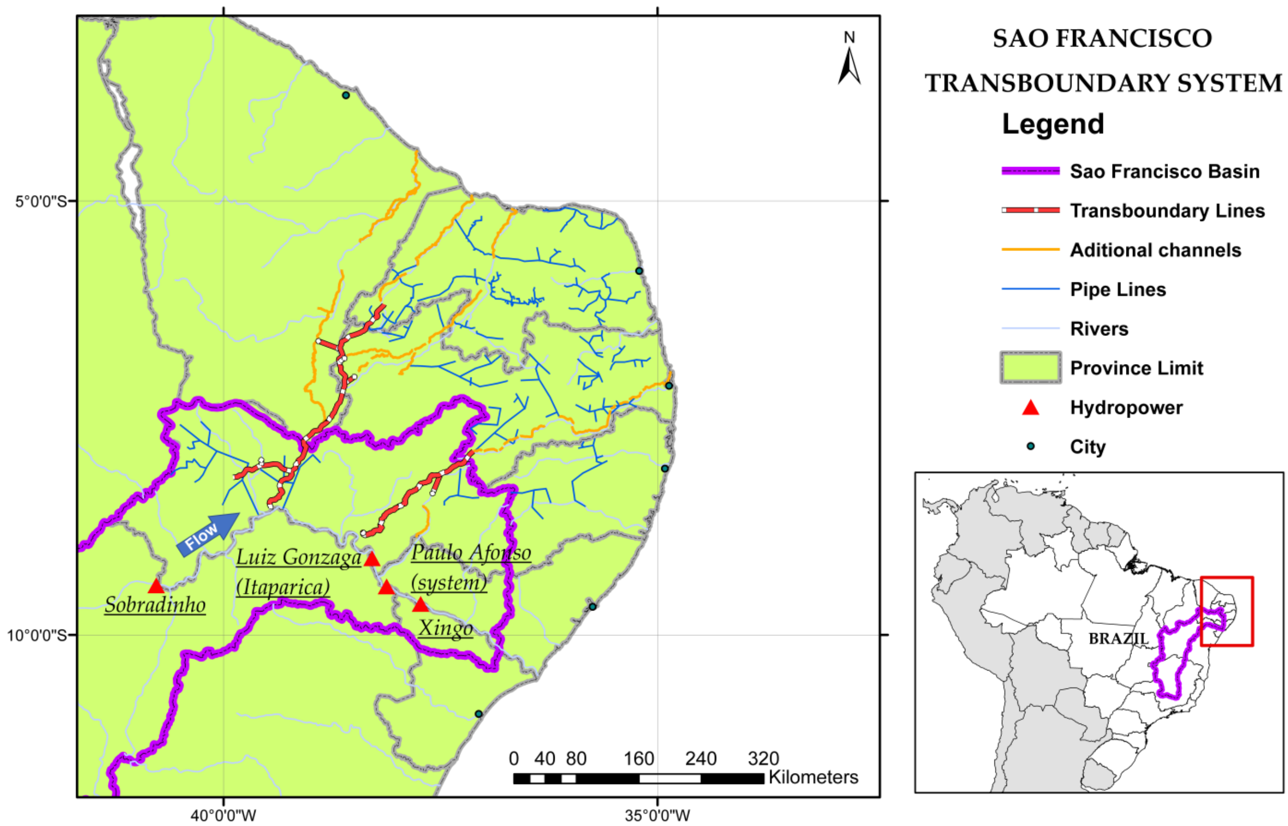

Figure 5. The São Francisco basin and its transboundary system.

2.3. Application of the Model

AcquaNetGIS and the proposed methodology using the avoided losses or revenue curve in the hydro-economic optimization of the allocation of water was applied to the São Francisco Transboundary System (SFTS). Figure 5 illustrates the location and the general system. The SFTS has two pipelines for delivering water to the semi-arid region of Brazil in the states of Pernambuco, Paraíba, Rio Grande do Norte, and Ceará. The total water extracted from the São Francisco River (SFR) has an installed capacity of 127 $m^3 \cdot s^{-1}$. The North Line has a main channel, 260 km in length, with 675 hm^3 of reservoirs, an installed pump capacity of 99 $m^3 \cdot s^{-1}$, and 170 m of elevation for water transposition. The East Line has a main channel with a length of 217 km with 38 hm^3 of reservoirs, an installed pump capacity of 28 $m^3 \cdot s^{-1}$, and 332 m of elevation for water transposition. The Supplementary Materials present a description of the area and the system.

The model was constructed according to the network presented in Figure 6. The hydropower reservoir considers the mean monthly evaporation. The areas upstream from the reservoirs and the water intake of the SFTS were considered as a water balance node. This node included the discharge input related to the incremental drainage area and the water demand for irrigation, urban supply, and other uses. As a result of the spatial distribution, all of the proposed reservoirs in the SFTS were considered to be equivalent reservoirs, represented as the total volume of the main reservoir for each line.

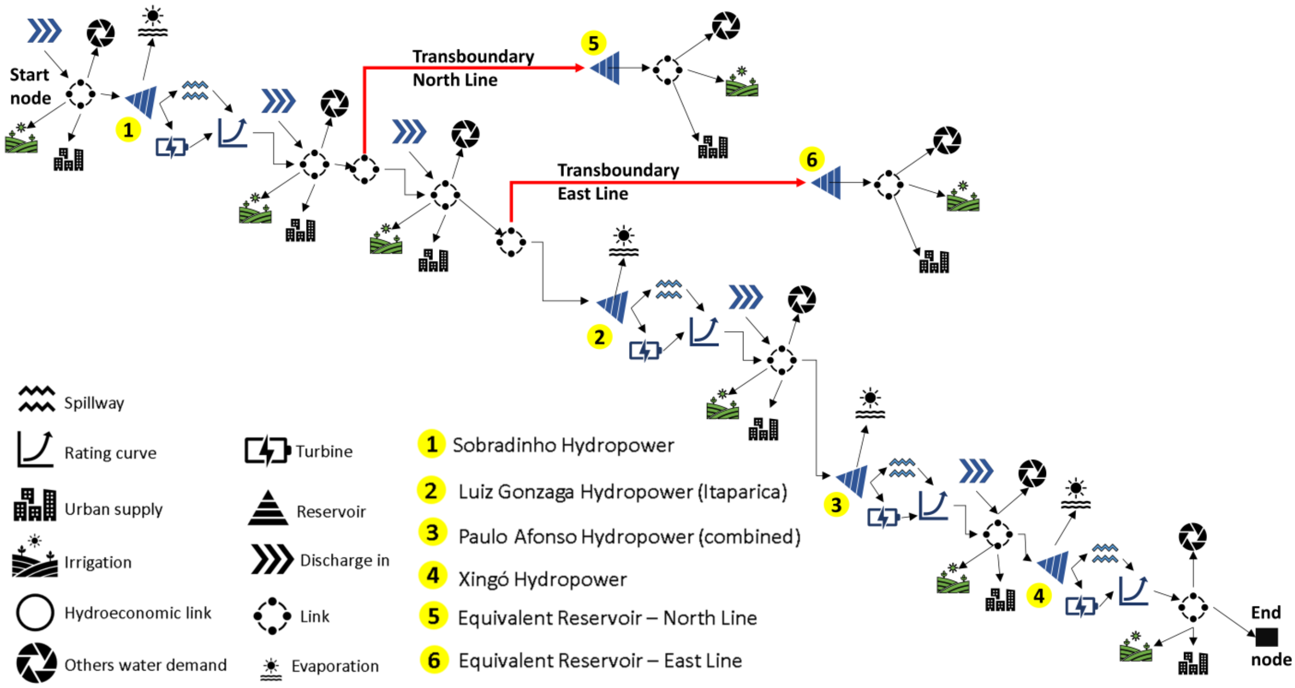

Figure 6. Topology of the São Francisco basin downstream from the Sobradinho hydropower and the transboundary system for optimization of the network flow.

The priority-based optimization considered the standard and legislated water rights for each sector, in the following order: (1) human and animal water supply; (2) irrigation; (3) energy generation; and (4) other users. The water demand curves based on the proposed method for hydro-economic optimization were simplified by using the revenue of each sector's production because of a lack of information. However, we judged that this simplification was permissible for presenting the proposed model and method to evaluate the results of the water allocation and the externalities in the decision-making process. The water demand curves of the proposed method used in the hydro-economic model are presented in Figure 7. The data sources and details of the water demand curves according to the proposed method are fully presented in the Supplementary Material (also see the Data Availability section). The SFTS can pump a high discharge when the Sobradinho reservoir is up to 94% of its total operational volume. The water extracted by the SFTS from the São Francisco River was ignored in order to understand the impact on the hydroelectrical generation. The area downstream from the Xingó hydropower station has a restriction that ensures a minimal flow of 800 $m^3 \cdot s^{-1}$ [62].

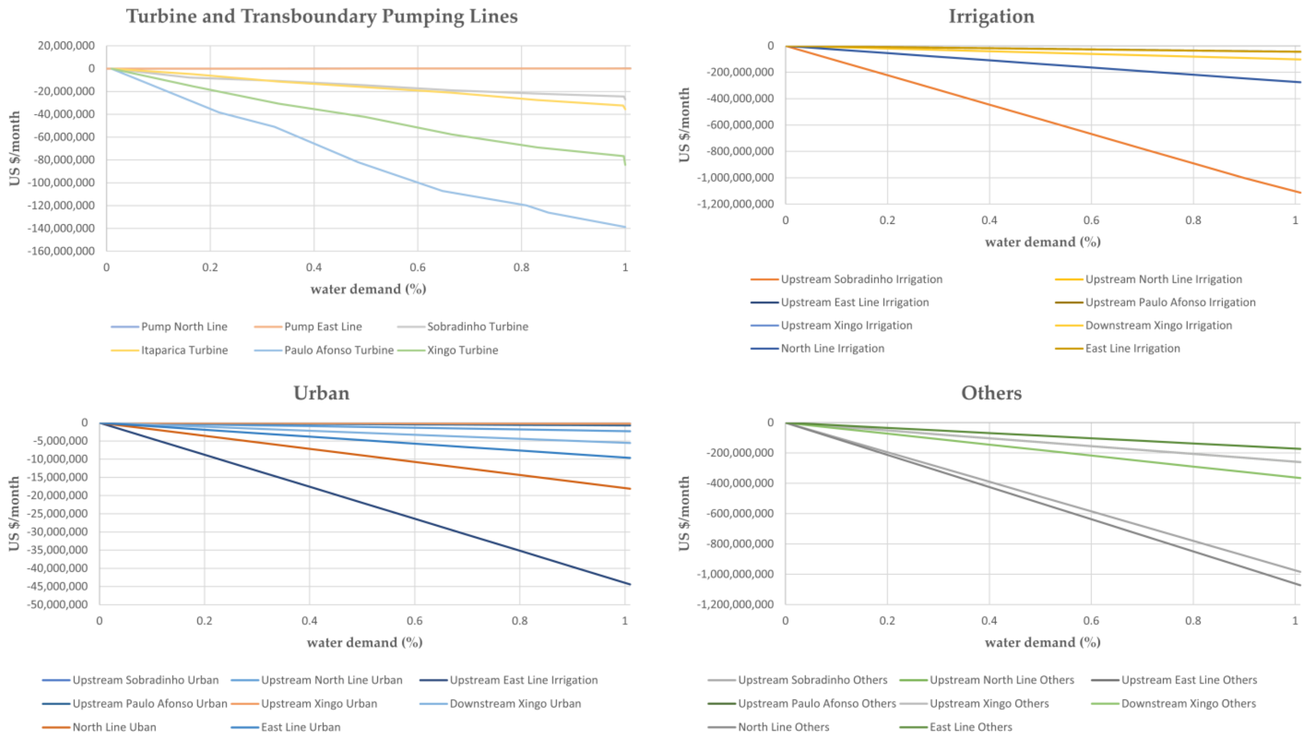

Figure 7. Revenue of each water demand sector and region in the application of the model (an alternative representation of the revenue curves is presented in the Supplementary Materials).

Priority-based and hydro-economic optimizations were carried out with two scenarios of water demand projected up to 2040. The scenarios were: A1: priority-based optimization and water demand to 2020; A2: priority-based optimization and projected water demand to 2040; B1: hydro-economic optimization and water demand to 2020; and B2: hydro-economic optimization and projected water demand to 2040. Table 1 shows the water demand for each region used in the application of the model for each scenario, based on [43]. Details on the water demand and dataset used as the models' input are presented in the Supplementary Materials, and the data are available at the code repository [44] and at GitHub (https://github.com/wdvichete84/sustainable_waterAllocation_model.git (accessed on 20 December 2022)). The total flow for the turbines in the hydropower stations uses the availability index to represent the operational time in each year. The Sobradinho hydropower station used an availability index of 89.4%, and the Itaparica (Luiz Gonzaga), Paulo Afonso System, and Xingó hydropower stations had 85.5%. The Paulo Afonso System and Xingó hydropower stations are run off river dams. The demand of the São Francisco Basin (SFB) downstream from the SFTS turbine is the cumulative flow for Itaparica, the Paulo Afonso System, and Xingó. The generation of hydropower electricity is a non-consumption water demand, meaning that the total cumulative flow is not the total flow required. The requirements of turbine flow and the total capacity are presented in the Supplementary Materials.

The hydro-economic optimization considered the revenue curves based on the production of goods and services (GDP) of each state (Bahia, Sergipe, Pernambuco, Paraíba, Rio Grande do Norte, and Ceará) using the data from [63] as the information for 2020. The region in Bahia is located upstream from the Sobradinho hydropower station and the North Line (which delivers water to Ceará), and has strong economic pressure for irrigation. Urban economic pressure is higher in the cities located between the Sobradinho hydropower station and the East Line's intake. Moreover, the East Line and the North Line create economic pressure for water supply, caused by the cities of Fortaleza, Mossoró, Juazeiro do Norte, Campina Grande, and João Pessoa (4.5 million urban inhabitants). The demand for irrigation and other users for water production represent higher revenues than turbines and urban supply. The values of the revenue for each type of water demand user were considered to be negative to simplify the calculations and maintain the objective function of the minimization of costs. The model aimed to achieve the minimum cost related to the total demand of water flow. However, the extraction of water by the North and East Lines of the SFTS involves a pumping system. The cost of pumping water to the SFTS was considered as a positive value, i.e., a penalty for delivery water to the line's infrastructure. The cost of pumping water was calculated on the basis of the water head and power used for pumping. The cost of hydropower and pumping water to the North and East Line has a mean energy price of 39.95 USD/MW. The power capacity of the turbines and the pumping system of the SFTS are presented in the Supplementary Materials. All of the scenarios and optimization kernels were calculated on the basis of the flow recorded in the SFB between January 1941 and June 2021, taking the mean monthly flow. Moreover, the model's time-step was set to monthly optimization.

Table 1. Summary of the water demand scenarios, in $m^3 \cdot s^{-1}$ (adapted from [43]).

Region	Type	2020 (A1 and B1)	2040 (A2 and B2)
SFB upstream of the SFTS	Turbine	3808.44	3808.44
	Irrigation	364.00	440.92
	Urban	24.48	29.62
	Others	20.01	24.21
SFB downstream of the SFTS	Turbine	8741.69	8741.69
	Irrigation	95.16	115.15
	Urban	17.94	24.70
	Others	5.14	6.23
North Line of the SFTS	Irrigation	36.6	52.11
	Urban	15.91	18.83
	Others	9.01	13.61
East Line of the SFTS	Irrigation	7.08	8.37
	Urban	5.74	7.02
	Others	4.44	5.74
SFB downstream from Xingó hydropower station	Restriction (minimum flow)	800.00	800.00

3. Results

The average flow rates to meet the demands are presented in Table 2, and the percentages of the total water required are shown in Table 3. The model based on priorities resulted in a low guarantee for meeting the demands of urban supply, irrigation, and other uses in the São Francisco basin in both scenarios, regardless of the transposition. The model calculated a guarantee of a 27.5% fulfillment for irrigation in the A1 scenario and 25.7% in the A2 scenario, when the water intake of the East Line was higher than the upstream irrigation by 16.9% and 15.5%, respectively. The best case was for the turbine flows downstream from the East Line's intake (91.2%) and upstream from the North Line's intake (77.6%), without the SFTS.

Table 2. Mean flow provided ($m^3 \cdot s^{-1}$) for the 2020 (A1 and B1) and 2040 (A2 and B2) scenarios.

Location	Type	Priority-Based Optimization				Hydro-Economic Optimization			
		Without SFTS		With SFTS		Without SFTS		With SFTS	
		A1	A2	A1	A2	B1	B2	B1	B2
SFB upstream from the SFTS	Turbines	2954.3	2836.2	2836.2	2836.2	3084.8	3084.7	3084.8	3055.5
	Irrigation	61.6	68.2	56.8	68.1	133.4	143.3	132.3	157.9
	Urban	4.6	4.9	4.1	4.8	6.4	7.8	6.3	7.3
	Others	3.8	4.1	3.3	4.0	9.0	10.9	9.0	10.5
SFB downstream from the SFTS	Turbines	7968.8	7726.3	7728.4	7728.9	8123.3	8096.9	8065.9	7955.4
	Irrigation	26.2	29.6	14.4	17.5	14.3	17.3	14.1	16.7
	Urban	3.4	4.1	3.4	4.1	3.2	3.9	3.2	3.7
	Others	0.7	0.8	0.7	0.8	1.2	1.4	1.2	1.4
North Line	Irrigation	-	-	12.9	17.7	-	-	32.9	46.3
	Urban	-	-	5.4	6.3	-	-	8.3	9.4
	Others	-	-	3.0	4.4	-	-	8.2	12.3
East Line	Irrigation	-	-	2.5	2.9	-	-	3.7	4.2
	Urban	-	-	1.9	2.3	-	-	3.0	3.5
	Others	-	-	1.5	1.9	-	-	2.7	3.4

Table 3. Fulfillment of the average flows of the São Francisco River basin and the SFTS, as percentages.

Location	Type	Priority-Based Optimization				Hydro-Economic Optimization			
		Without SFTS		With SFTS		Without SFTS		With SFTS	
		A1	A2	A1	A2	B1	B2	B1	B2
Upstream from the SFTS	Turbines	77.6%	74.5%	74.5%	74.5%	81.0%	81.0%	81.0%	80.2%
	Irrigation	16.9%	15.5%	15.6%	15.4%	36.6%	32.5%	36.4%	35.8%
	Urban	18.6%	16.6%	16.6%	16.2%	26.1%	26.2%	25.6%	24.7%
	Others	18.9%	16.8%	16.7%	16.4%	45.0%	44.9%	44.7%	43.5%
Downstream from the SFTS	Turbines	91.2%	88.4%	88.4%	88.4%	92.9%	92.6%	92.3%	91.0%
	Irrigation	27.5%	25.7%	15.2%	15.2%	15.0%	15.0%	14.8%	14.5%
	Urban	19.1%	16.5%	18.8%	16.5%	17.8%	15.6%	17.6%	15.1%
	Others	13.9%	13.0%	13.2%	13.1%	22.6%	22.6%	22.6%	22.4%
North Line	Irrigation			35.3%	34.1%			89.8%	88.9%
	Urban			33.9%	33.2%			51.9%	49.9%
	Others			33.4%	32.5%			91.1%	90.0%
East Line	Irrigation			35.2%	34.5%			51.9%	50.0%
	Urban			33.7%	33.0%			51.7%	49.8%
	Others			33.3%	32.4%			61.0%	59.5%

The priority-based optimization resulted in the best ability to fulfil the water requirements of the São Francisco Basin (SFB) without the SFTS in both scenarios. In Scenario A1, the water supply was, on average, 3.1% higher without the SFTS, with the biggest difference (12.3%) observed for the irrigation demand downstream from the East Line, while the others ranged between 0.3% and 2.2%. In the A2 scenario, the average guarantee of service was 1.4% higher, with the biggest difference (10.6%) for the irrigation downstream from the

SFTS, while the others were smaller than 0.4%. The turbine flow upstream of the North Line without the SFTS was 3.1% higher for Scenario A1, while that of the flow downstream from the intake was 2.8%.

In general, the hydro-economic model also had low guarantees to provide water for the users' water demands. However, the simulation without the SFTS resulted in higher guarantees of fulfillment in both scenarios, with the exception of the upstream irrigation in Scenario B2, where the difference was 3.3% greater with the SFTS. Urban supply, irrigation, and other upstream water demands had higher guarantees, except for the downstream flows of turbines, for which the guarantees were 92.9% in Scenario B1 and 81% in Scenario B2, without the SFTS. The guaranteed provision of water for the downstream turbine flows was 11.9% (B1) and 11.6% (B2) higher than for those upstream without the SFTS, and 11.3% (B1) and 10.8% (B2) higher with the SFTS.

The guarantees to fulfill the SFTS's water demands in the two lines were, on average, 18.2% (A1) and 17.8% (A2) greater than those of the SFB in the priority-based optimization, and 39.3% (B1) and 38.7% (B2) greater in the hydro-economic optimization. The highest guarantees of fulfillment determined for the North Line in the hydro-economic optimization were for irrigation (89.8% under B1 and 88.9% under B2) and other demands (91.1% under B1 and 90% under B2).

The flow duration curves produced by AcquaNetGIS for the outlet of the network flow are presented in Figure 8. The priority-based optimization determined flows between 4186.3 $m^3 \cdot s^{-1}$ and 14,826.7 $m^3 \cdot s^{-1}$ for 26.8% of the time, and between 1408.0 $m^3 \cdot s^{-1}$ and 2373.5 $m^3 \cdot s^{-1}$ for 25.2% of the time. This model made a larger volume of water available (616,537.8 hm^3) for the São Francisco Basin's outflow node for a longer time (52%) than the hydro-economic optimization, implying a lower fulfillment of the demands of the SFB and the SFTS. The guarantee to meet the restricted flow rate (800 $m^3 \cdot s^{-1}$) was 99.01% for the hydro-economic optimization and 98.48% for the priority-based optimization.

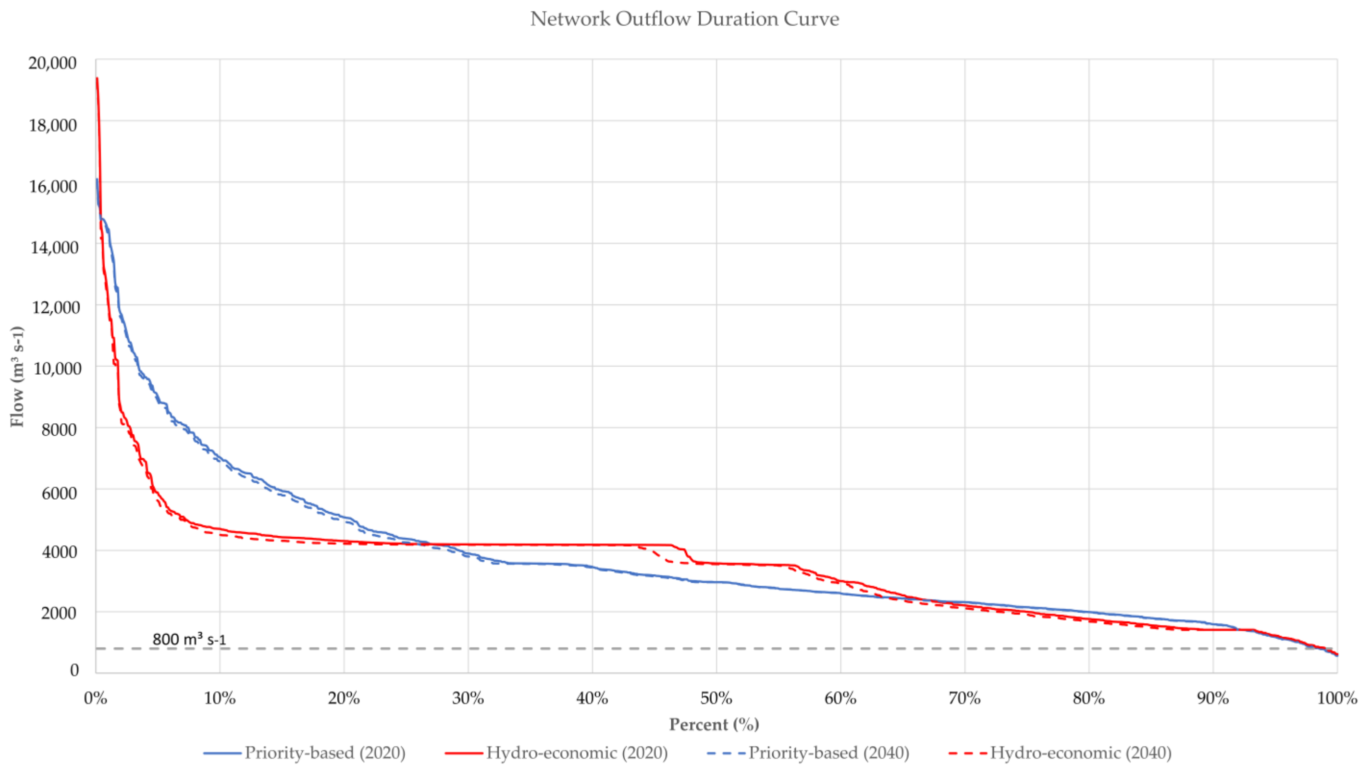

Figure 8. Flow duration curve at the outflow node.

4. Discussion

The proposed AcquaNetGIS model for water allocation was built using a linear programming optimization kernel. The model can be configured to simulate daily, monthly, and even annual time-steps. The optimization occurs at each time-step, which can make the optimization less efficient compared with methods that perform global optimizations. A user interface for the input, calculation, and analysis of the results is under development and will be made available in the same repository as the model built for the SFTS application.

The direct relationship between the water available to a user sector and the generated revenue that was used in the application of the model was simplified to a linear relationship. Hydroelectric energy generation used a discharge rating curve downstream from the hydropower station, and the potential energy of the generation was the water level in the reservoir and the water level in the river in a downstream section. The water demand for urban supply and irrigation considered a linear relationship between the revenue generated and the estimated water demand [28].

The water flow for irrigation was an average monthly value based on the total annual volume estimated for the demand of irrigation demand. However, there are crops that require additional water for irrigation in specific periods of the year, depending on the water deficits. This can result in a more flexible allocation of water for other demands in the period when crops do not need supplementary irrigation, but it can also increase the competition for water in periods of water scarcity. The authors of [36] presented a formula for estimating crops' water requirements. This method was based on the growth function of the crop species and the water deficit in the soil. This type of method can be used when sufficient data are available for its application.

The flows demanded in the transposition lines were the demands for additional water made available by the SFTS. In this study, no water balance analysis considering the availability of water in the receiving basins was carried out. Energy generation was not considered in the demands of the receiving basins. The challenges of operating and managing the reservoirs and pumping systems in the transposition system were highlighted because of their magnitude and spatial distribution, as well as maintaining security to avoid the unauthorized withdrawal of water from the system. The reservoirs of each line of the transposition system were simplified using an equivalent reservoir. Due to the uncertainties between the original design and the as-built design of these structures, the evaporation from these reservoirs was disregarded.

At present, pumping above the average flows established in the operational rules of the SFTS can only occur when the Sobradinho reservoir holds at least 94% of its total volume. When this rule is disregarded, it is possible to analyze the results and impacts on the Sobradinho reservoir without the operation of the rule. It was possible to observe that the reservoir's volume varied towards the maximum more frequently in the hydro-economic model than in the priority model. Figure 9 shows the Sobradinho reservoir's volume according to the operational rule of the SFTS, and the differences between the hydro-economic and priority-based optimizations.

The minimum flow at the end of the network represents a policy that considers the flows downstream from Xingó. The authors of [41,64] pointed out that the minimum flow at the end of São Francisco River has the objective of keeping the minimum required by the ecosystem and preventing the intrusion of salt. Environmental flows were not considered in the application of the model. The Hydrological Alteration Index proposed by [65] requires a hydrological minimum regime, which is different from the minimum flow considered. The hydrological alteration in the São Francisco River has been noted since the construction of the Três Marias (1952) and Sobradinho (1979) hydropower stations. The hydrological regime to achieve the requirements of hydropower flow conflict with urban supply, irrigation, and the minimum flow at the end of SFR [64]. The authors of [62,64] highlighted the main problems caused by alterations in the hydrological flow regime that have impacted the SFR downstream from the Xingó hydropower station, including: (i) a low water volume in the main channel; (ii) interruption of the natural cycle of lateral wetlands;

(ii) bank erosion; (iii) loss of irrigation areas; (iv) impacts on the infrastructure of water extraction; and (v) failure of containing dikes. As presented in the Supplementary Material, the natural long-term average monthly discharge downstream from the Xingó hydropower has decreased from 5000 $m^3 \cdot s^{-1}$ to 2600 $m^3 \cdot s^{-1}$ (a 48% reduction). A comparison of the periods between 1941 and 1950 and between 2009 and 2018 (before the SFTS started operating) shows that the average monthly discharge decreased by 59%. Using 90% of the flow duration curve, the natural average monthly discharge decreased by 67% (from 2917 $m^3 \cdot s^{-1}$ to 966 $m^3 \cdot s^{-1}$). The changes in the patterns of the runoff indicate that the São Francisco River has changed its hydrological regime as a result of other possible causes, such as land use changes and climate change [66,67]. An alternative solution for the operational rule of the SFTS should be taken into account for the altered hydrological regime and the results of the hydro-economic optimization.

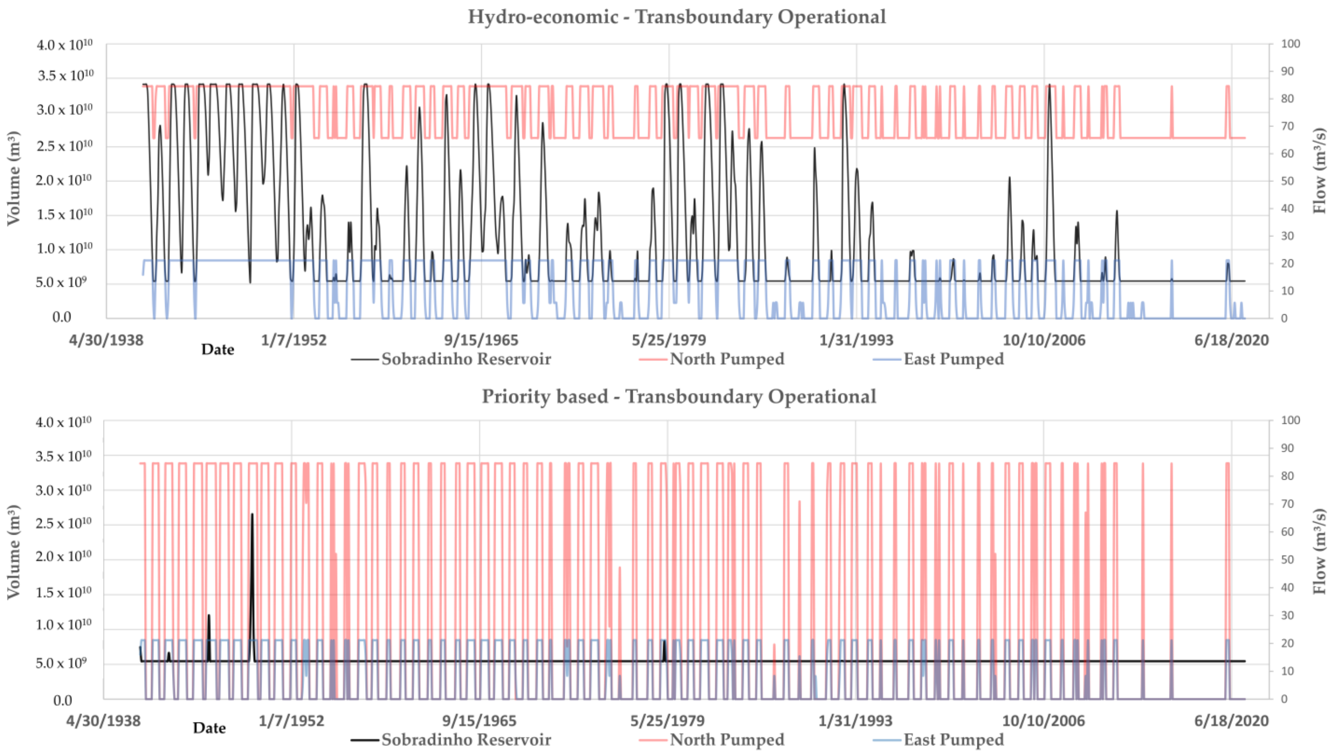

Figure 9. Operation of the Sobradinho reservoir without using the operational rule, based on the results of applying the AcquaNetGIS model.

Sustainability can have different dimensions in water allocation [37,68]. According to [69], the dimensions and characteristics observed by the sustainability indicators can include social, physical, environmental, and cultural concepts. The authors of [70] proposed a sustainability indicator based on water availability, composed of the indicators of resilience, vulnerability, and reliability [71]. These indicators help in our understanding of the results by considering their occurrence in the simulated time-period. For example, even if the average flow available for a demand is lower than the total flow demanded, resilience allows an evaluation of the probability that the system will be able to meet this demand (satisfactory and unsatisfactory states). Reliability, on the other hand, can demonstrate, in percentage terms, how the demand was met in the simulated period. On the other hand, vulnerability shows the severity of the non-fulfillment of the demands. The use of the average flow available for each demand by the model can lead to an interpretation of the non-fulfillment of demands; however, the demands of urban supply, other users, and irrigation were fully met in most humid periods (with a greater availability of water).

To evaluate this variability and seasonality in the fulfillment of demand, the evaluation indicators proposed by [71] and the sustainability index [70] were used. Figure 10 presents the sustainability index calculated for the 2020 and 2040 water demand scenarios and for both optimization models (priority-based and hydro-economic). In general, the hydro-economic optimization achieved better sustainability in relation to the worst-case scenario. In this optimization, the resilience reached higher values than in the priority-based optimization for all users, thus increasing the reliability and significantly reducing the vulnerability of meeting the demands of all the user sectors.

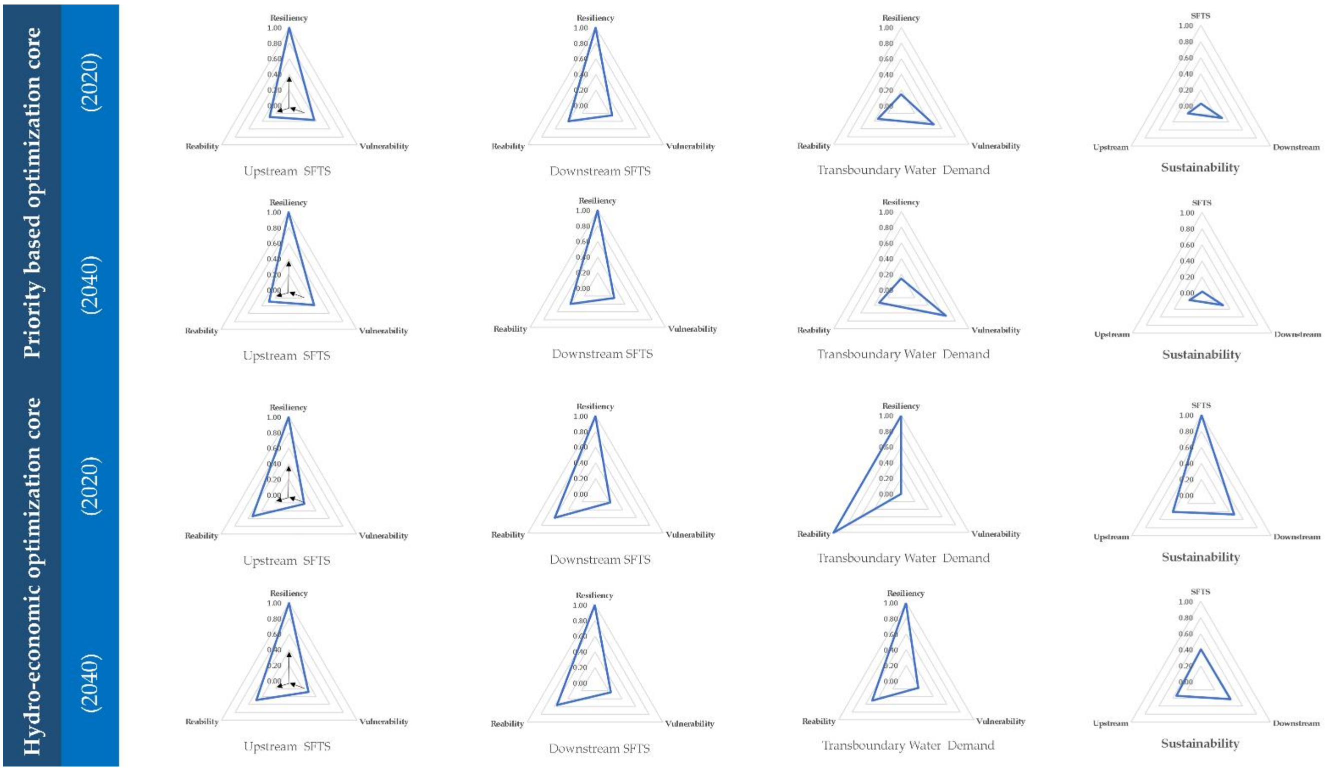

Figure 10. Sustainability indicators based on the results of applying the AcquaNetGIS model (an alternative representation of the revenue curves is presented in the Supplementary Material).

In general, both optimization alternatives presented low guarantees of fulfillment for the water demand, but the guarantees were higher in the São Francisco Basin, with the exception of urban supply and irrigation downstream of the SFTS, with and without the transposition. The hydro-economic optimization resulted in a 7% higher volume of water allocation than that of the priority-based optimization for irrigation, urban supply, and hydropower. This is because the costs in the network used by the hydro-economic optimization takes a systematized approach for all water demands and, therefore, becomes more sensitive in allocating the water through the network flow. The revenue curves and the differences between the results of the water allocation for the priority-based optimization and the hydro-economic optimization in the SFTS show an average annual economic benefit of up to 1.44 billion USD. However, establishing an institutional policy framework for the cross-incentives of the economic benefits of water used for economic production is challenging. Further analyses must consider parameters such as the socio-cultural context, the generational context, public policy, alternative energy production, different operational rules, and alternative sources of urban supply. Multicriteria decision-making methods should consider the results of the proposed models in order to understand the stochastics of the hydrological regimes and economic production based on the availability of water. We suggest that future research should evaluate the non-linearities in the avoided loss curves and dynamic programming in the optimization kernel of the proposed model. Moreover, scenarios of climate change and public policy rules should also be tested.

5. Conclusions

The proposed AcquaNetGIS model is an engineering approach to using hydro-economic optimization for water allocation and decision support systems. The results of this model provide valuable information for decision-making and for stakeholders. Economic information and their externalities based on the production function improve the process of planning and carrying out the allocation of water in complex water resource systems and minimize the conflict caused by water scarcity. The hydro-economic optimization kernel has the ability to use the avoided loss or revenue curves based on a sector's production in the proposed method instead of the marginal benefits curves based on water demand. The proposed model and method were applied to the São Francisco Transboundary System. The AcquaNetGIS hydro-economic optimization provided 7% more water than the priority-based optimization. Both optimizations meet the minimal outflow node by 98.5% (priority-based) and 99.0% (hydro-economic) in the period of the simulation between January 1941 and June 2021. The application of the model to the São Francisco Transboundary Basin showed a trade-off between the water demand of irrigation in the SFB upstream from the Sobradinho hydropower station and the intake of the North Line, and the water demand for all users in the SFB downstream from the SFTS (irrigation, urban supply, and energy generation). We are aware of the model's limitations and uncertainty; however, considering the simplifications, the hydro-economic and the systematization of the structure to include the economic externalities and water demand pressure present a valuable and practical solution for the allocation of water. The hydrological alterations observed in the São Francisco River strongly suggest that the SFTS should have an alternative option for the operational rules that considers the results of the hydro-economic optimization. Institutional and policy regulations need to be improved to ensure the sustainability of the São Francisco Transboundary Basin, and the hydro-economic optimization results must be considered when planning the allocation of water planning and establishing sustainable operation rules for irrigation, water supply, and energy security.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/w15061170/s1, Figure S1: Daily flow input for model application upstream of Sobradinho Hydropower; Figure S2: Daily flow input for model application upstream of North Line water abstraction; Figure S3: Daily flow input for model application upstream of Itaparica Hydropower; Figure S4: Daily flow input for model application upstream of Paulo Afonso System Hydropower. Figure S5: Daily flow input for model application upstream of Xingó Hydropower. Figure S6: Revenue curve for Hydropowers and Pumping Stations of SFTS; Figure S7: Revenue curve for Irrigation; Figure S8: Revenue curve for Urban supply; Figure S9: Revenue curve for others water uses; Figure S10: Average Monthly Flow at Downstream of Xingó Hydropower; Figure S11: Flow duration curve in 10 years' time frame; Table S1: Summary of North line characteristic; Table S2: East line characteristic summary; Table S3: Hydropower characteristics; Table S4: Reservoir Elevation-area-volume; Table S5: Turbine efficiency and availability index; Table S6: Average Monthly evaporation for each reservoir (mm). Reference [72] is cited in the Supplementary Materials.

Author Contributions: Conceptualization, W.D.V. and A.V.M.J.; formal analysis, W.D.V.; funding acquisition, W.D.V. and A.V.M.J.; investigation, G.A.d.S.S.; methodology, W.D.V. and A.V.M.J.; resources, G.A.d.S.S.; software, W.D.V. and G.A.d.S.S.; supervision, A.V.M.J.; validation, A.V.M.J. and G.A.d.S.S.; visualization, G.A.d.S.S.; writing—original draft, W.D.V. and A.V.M.J. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by CAPES (grant number 88887502612/2020-00).

Data Availability Statement: The data that support the findings of this study, the model's documentation, the supplementary material, and the source code are openly available at https://github.com/wdvichete84/sustainable_waterAllocation_model.git (accessed on 20 December 2022) and [44].

Acknowledgments: We appreciate all the support from the LabSid team, especially Lina Maria Osorio Olivos.

Conflicts of Interest: The authors declare no conflict of interest.

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