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Effects of an outflow regime adoption of the São Francisco River reservoir system to meet water demands for multiple uses

Efeitos da adoção de um regime de defluência do sistema de reservatórios do rio São Francisco, para atendimento às demandas dos múltiplos usos da água

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ABSTRACT

The establishment of reservoir operation rules is a strategy used to increase storage volumes and satisfy water demands. However, these rules are not always compatible with the flow regime required to meet environmental needs. This paper aims to evaluate the effects of an outflow regime adopted by the São Francisco River reservoir system, which includes environmental water requirements, in the current laws for meeting water demands for multiple uses, according to Resolution 2081/2017 of *Agência Nacional de Águas* - ANA. The methodology adopted was the construction and simulation of alternative outflow operation scenarios, for a regular and a dry hydrological period, which were the following: 1) Outflow scenario according to Resolution 2081/17 and (2) Outflow scenario that considers a proposed environmental flow hydrogram for the low course of the São Francisco river. The operation effects in the meeting of multiple water uses were quantified in each scenario and compared with each other. The results suggest that when the maintenance of the aquatic ecosystems is a priority, the system demonstrated low water security in meeting the reservoirs target volumes and satisfying water demands, including the environmental flows.

Keywords: Reservoir operation; Environmental flows; Multiple water uses; Water scarcity; São Francisco River Basin.

RESUMO

O estabelecimento de regras de operação de reservatórios é uma estratégia utilizada para incrementar os volumes de armazenamento e viabilizar o atendimento das demandas de água. Entretanto, nem sempre estas regras são compatíveis com o regime de vazões requerido para o atendimento da demanda ambiental. Neste contexto, este artigo tem como objetivo avaliar os efeitos da adoção de um regime de defluência, do sistema de reservatórios do rio São Francisco, que inclua as demandas do ecossistema aquático, nas atuais diretrizes de atendimento das demandas de múltiplos usos da água, conforme a Resolução 2081/2017, da Agência Nacional de Águas - ANA. A metodologia adotada foi a construção e simulação de cenários alternativos de defluências para um período hidrológico normal e outro seco, que foram os seguintes: (1) Cenário de defluências que atende a Resolução 2.081/17 e (2) Cenário de defluências que considera um hidrograma ambiental proposto para o baixo curso do rio São Francisco. Os efeitos da operação no atendimento aos múltiplos usos da água foram quantificados em cada cenário e comparados entre si. Os resultados apontaram que ao priorizar a proteção dos ecossistemas aquáticos, o sistema demonstrou menor segurança hídrica para atender os volumes metas dos reservatórios e demandas de água, inclusive a demanda ambiental.

Palavras-chave: Operação de reservatórios; Hidrograma ambiental; Múltiplos usos da água; Escassez hídrica; Bacia hidrográfica do rio São Francisco.

INTRODUCTION

Reservoirs have a relevant function for water resource management, since they are structural solutions that offer several benefits, including the capacity to provide greater water availability by reducing the temporal variability of flow, which facilitates meeting demands for multiple uses (human supply, irrigation, industry, electric power, support aquatic ecosystems downstream, among others). Nevertheless, the reservoir management becomes a difficult assignment under circumstances where there are abrupt changes in water availability caused by climate change (World Water Assessment Programme, 2012; World Economic Forum, 2016). In periods of prolonged drought, for instance, there is a decay of the affluent flows to the reservoirs. Excessive use of this resource often hinders the recovery of stored volumes and produces water deficits.

Water deficits are characterized by an imbalance between water availability and demand, called "water scarcity" (Pedro-Monzonís et al., 2015; Sayers et al., 2016; Degefu et al., 2016). Water scarcity promotes conflicts among uses of this resource, which requires water management institutions to implement strategies to avoid or mitigate its effects (Martin-Carrasco et al., 2012; Spiliotis et al., 2016; Sayers et al., 2016). One of these measures is the establishment of operating rules for reservoirs. An approach considered capable of increasing water security in terms of the maintenance of stored volumes and providing sufficient water availability to meet current and future needs.

However, one of the greatest difficulties in the field of water resources management is to design and implement management programs that define the storage and withdrawal of water for anthropogenic uses with minimal damage to the environment, since the alteration of the natural runoff from the river can cause the degradation of aquatic ecosystems. Thus, authors such as Sayers et al. (2016) point out that, in a period of reduced water availability, meeting environmental demands is generally neglected, through the establishment of stricter operating conditions for reservoirs. These conditions are established in order to prevent water losses and enable reservoirs to maintain storage levels above the minimum limits specified to ensure compliance with the operational restrictions of the system. In order to achieve this purpose, a strategy is to make the minimum outflow restriction more flexible, since smaller outflows are able to help with in the balance between the water inputs and outputs of the reservoir. Therefore, this type of emergency strategy promotes the reduction of water deficits from the volumes stored at the expense of environmental health.

Bunn & Arthington (2002) defined four principles that describe the influence of the river flow regime on the complexity of aquatic biodiversity (1- flow regime is a physical parameter that affects the biotic diversity; 2- aquatic species develop life history patterns based on the flow regime; 3- the longitudinal and lateral connectivity of the river are important for the maintenance of some species; 4- altered flow regimes enable the exotic species invasion). According to the authors, the change in flow patterns of the natural river regime, such as seasonality and predictability, which associates the variability of flows with the life histories of aquatic species. Many of these species are adapted to a regularity of hydrological events, such as flood and drought periods, which serve as triggers to initiate certain stages of their life cycle, for example the recruitment and spawning of fish.

The importance of seasonality and variability of the river regime is highlighted by the concept of environmental hydrogram, which according to The Brisbane Declaration (2007, p.1), is defined as "the quantity, timing, and quality of water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend on these ecosystems".

Water quality is another characteristic affected by changes in the outflow regime of reservoirs. The reduction in the magnitude of the flow not only causes an increase in the concentration of pollutants, but also allows the intrusion of the saline wedge into the river, which produces an increase in salinity levels. Some aquatic species are more sensitive to changes in quality standards, resulting in loss in biodiversity and ecosystem services (Wang et al., 2015; Mosley, 2015; Huang et al., 2015; He et al., 2018; Fonseca et al., 2020).

Meeting the demands of the aquatic ecosystem with the adoption of the environmental hydrogram, as an outflow rule may restrict the operational performance of reservoirs, penalizing other multiple uses, especially in periods of low availability (Pang et al., 2013; Bonsch et al., 2015; Liechti et al., 2015; McManamay et al., 2016; Brambilla et al., 2017; Li et al., 2018).

It is necessary to evaluate the effects of adopting environmental hydrogram as an outflow rule in meeting the multiple uses, even during a limited water availability condition. For this purpose, this paper intends to evaluate a decision-making process for reservoir operation rules designed based on a strategy to mitigate a water scarcity effects. In addition, this study contemplated an operation mode which considers an environmental hydrogram and it was compared with the other modes of operation practiced in the system under study, in order to identify potential conflicts and the viability of integrating the meeting of environmental demand with the set of operational rules for meeting multiple uses proposed by the current law.

There is a wide variety of studies that have proposed different approaches that seek to balance the environmental and socio-economic needs associated with reservoir operation strategies. Martin et al. (2016) used multi-criteria analysis involving socio-environmental issues in the management of water resources, while Pang et al. (2013) presented an economic compensation in order to implement an environmental flow regime and Li et al. (2018) used the Indicators of Hydrologic Alteration (IHA) to evaluate the operation of reservoirs that integrate the objectives of hydroelectric power production and environmental demand.

The São Francisco river water system is suitable as a case of study, due to the fact that its reservoir complex has great importance as a fresh water source for meeting multiple uses in the Northeast region of Brazil (Agência Nacional de Águas, 2017a).

Since 2013 in the São Francisco river basin, it has been facing a critical period of water scarcity, producing the inflow to its main reservoirs with average values considered as the worst in the history for the period from 1931 to 2018 (Agência Nacional de Águas, 2018). This situation resulted in a significant reduction in the water stocks of these structures, which led the *Agência Nacional de Águas* (ANA) to reformulate the operating rules of the reservoirs in this basin. The first action carried out was the flexibilization of the restriction of the minimum outflows for the Sobradinho and Xingó reservoirs, which were 1,300 m^3/s and became 1,100 m^3/s (Agência Nacional de Águas, 2013). As there was no significant improvement in the hydroclimatic situation in the region, successive flexibilizations were necessary, and the smallest of them occurred in July 2017, with a minimum restriction flow rate of 550 m^3/s (Agência Nacional de Águas, 2017a). These minimum flow flexibilizations contributed to the reduction of deficits, allowing greater water availability for the system. However, the consequences of outflows practiced resulted in the reduction of water depths downstream of the reservoirs. This subsequently created several inconveniences to water users, in the lower stretch of the river, especially the degradation of water quality for the supply of riparian communities (Fonseca et al., 2020).

ANA elaborated the Resolution Nº 2081 of December 4, 2017 (Agência Nacional de Águas, 2017b) as a mitigation measure for possible future shortages. The Resolution 2081/17 provides the conditions for the operation of the São Francisco River water system, considering the critical scenario of water scarcity in the basin and aimed to increase water security and ensure the provision for multiple uses. Furthermore, this resolution establishes that the minimum outflows should vary according to the volume levels stored in the reservoirs.

In this condition, the operating rule recommends the maximization of water stocks as a strategic reserve for the dry season. It is worth noting that although the change in the rules of minimum outflow restriction of Sobradinho and Xingó reservoirs has provided positive effects on the increase in storage volumes of reservoirs (Agência Nacional de Águas, 2018), these rules did not incorporate the dynamics of the natural flow regime required for the preservation of aquatic ecosystems.

In spite of the Federal Law of Waters nº 9.433/97 (Brasil, 1997) to define that, in periods of water scarcity, the attendance of water demands for human consumption and animal feed is priority, it is necessary to guarantee environmental preservation. The maintenance of aquatic ecosystems is integrated with the "Seventeen global goals for sustainable development", presented by the United Nations (2017). Goal six, called "Clean water and sanitation", provides a set of targets, among them ensuring sustainable withdrawals of this resource to protect and restore aquatic ecosystems.

MATERIAL AND METHODS

This study consists of analyzing two groups of alternative outflow scenarios, with the first group considering a period with a normal hydrological condition, which includes the years 2008 to 2011, and the second considering the dry years 2013 to 2018.

The selection of the analysis periods was based on a statistical study for the classification of years with high and low water availability, by means of time series of naturalized flow of Sobradinho Reservoir (Sistema de Acompanhamento de Reservatórios, 2019), illustrated in Figure 1. The methodology adopted was "water condition of the watershed" (CHID), developed by Genz & Luz (2007).

Thus, the years from 2013 to 2018 presented six consecutive years with "dry" and "very dry" classification. Considered a critical situation, since the previous period with lower water availability was only three years (2001 to 2003).

As for the period of years classified as normal, it was opted for the years prior to the selected dry period, between 2008 and 2011.

The alternative outflow scenarios for the dry and normal periods describe two different rules for the operation of the São Francisco River reservoir complex, the first of which represents the reservoir operating restrictions established by Resolution No. 2081 of December 4, 2017; and the second refers to the operating restrictions that respect the natural seasonal outflow of the low course of the São Francisco River, represented by the environmental hydrogram proposed for this stretch (Medeiros et al., 2010).

To support the analysis of each scenario, the technical procedure adopted was mathematical modeling through a flow-network model.

In order to achieve the objectives specified in this study, the methodology was outlined in three stages: (1) Data collection, organization and analysis; (2) Construction of alternative outflow scenarios; (3) Simulation and prospection of the alternative scenarios.

The following topics have a brief description of each methodological step, as well as a characterization of the area of study.

Area of study

The São Francisco river basin has a drainage area of 639,219 km^2, occupying seven Brazilian states (Minas Gerais, Bahia, Distrito Federal, Goiás, Pernambuco, Sergipe and Alagoas), which corresponds to 7.5% of the Brazilian territory, 58% of which is

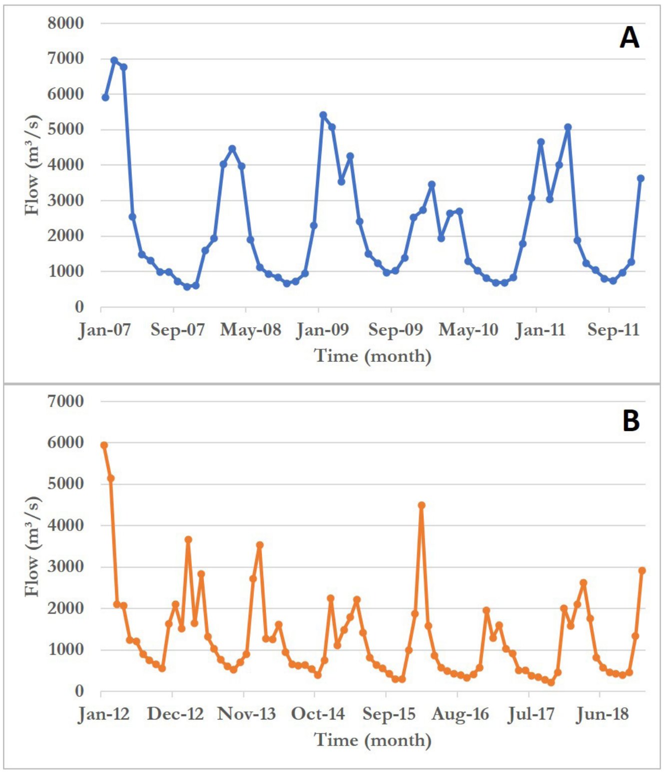

Figure 1. Sobradinho Reservoir Naturalized Flow. (A) Normal hydrological condition; (B) Dry hydrological condition.

located in the semi-arid region (Agência Nacional de Águas, 2015). According to Figure 2, this basin is divided into four physiographic regions (Upper, Central, Sub-Central and Lower São Francisco).

The water system of the São Francisco River basin consists of seven reservoirs of great importance, located in the main river channel, three of which have storage capacity (Três Marias, Sobradinho and Itaparica) and the others operate by run-of-river system (Paulo Afonso-Moxotó Complex and Xingó).

The reservoirs of Três Marias and Sobradinho regularize the flow of the São Francisco River and enable the operation of downstream reservoirs. Whereas the Três Marias reservoir has a surface area of 1040 km^2 and maximum evaporation rates of 61 mm/month (May and June) and 58 mm/month (July), the Sobradinho reservoir has higher evaporation loses, with maximum taxes of 234 mm/month (September), 267 mm/month (October) and 245 mm/month (November) and a surface area of 4,214 km^2

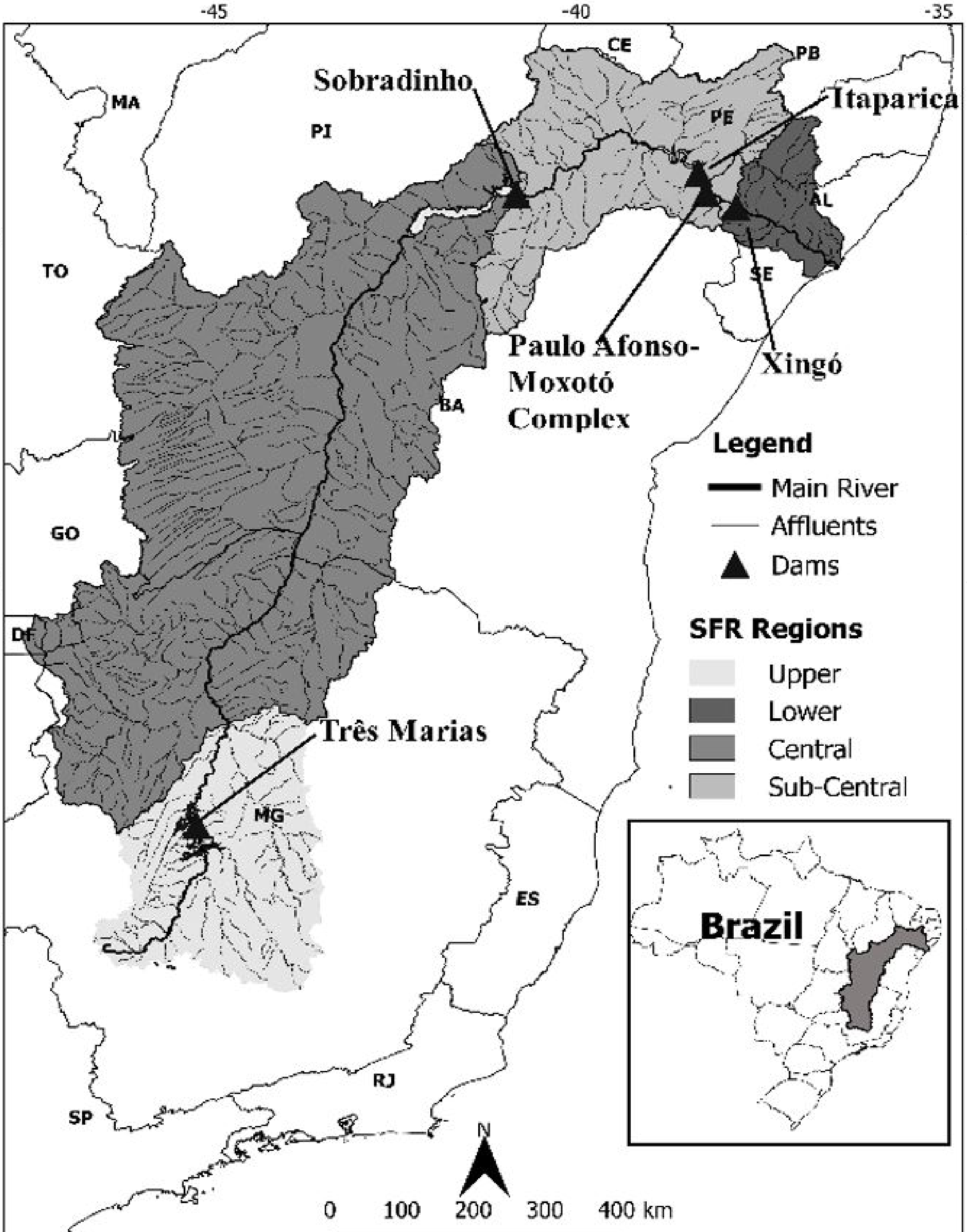

Figure 2. Physiographic division and location of the main reservoirs of the São Francisco River basin (Source: Authors adaptation Comitê da Bacia Hidrográfica do Rio São Francisco, 2016).

(Operador Nacional do Sistema Elétrico, 2004; Comitê da Bacia Hidrográfica do Rio São Francisco, 2016). By this fact and due to Três Marias dam is located in the Upper São Francisco, a physiographic region with the highest average rainfall in the basin (Agência Nacional de Águas, 2017b), the operating rules for this reservoir aim to maximize its water storage and ensure sufficient supply to meet the demands of multiple uses in critical periods (Operador Nacional do Sistema Elétrico, 2015).

Table 1 presents the operational characteristics of the main reservoirs, such as live storage, elevation and volumes.

Among the most significant consumptive uses in the basin, irrigation is noteworthy, with about 79% of the flows withdrawn in 2014 (Comitê da Bacia Hidrográfica do Rio São Francisco, 2016), and this is one of the sectors that mostly promotes socioeconomic development in the region and is expanding. Between 2004 and 2013, for example, there was an approximate growth of 136% in the total number of irrigated areas (Comitê da Bacia Hidrográfica do Rio São Francisco, 2016).

Regarding non-consumptive uses, the basin has 40 reservoirs with hydroelectric use, and the plants with higher installed power are located in the main channel of the river and are part of the *Sistema Interligado Nacional* (SIN), which is responsible for generating and transmitting electric power in Brazil. The hydroelectric plant of Três Marias belongs to the Southeast/Center-West subsystem and the other reservoirs (Sobradinho, Itaparica, Paulo Afonso Complex and Xingó) are part of the Northeast Subsystem and also responsible for most of the hydroelectric energy generated for the northeast region of the country (Agência Nacional de Águas, 2015).

Data collection, organization and analysis

The data acquired to support this study consist of information that was included in the flow-network model, as described in Figure 3.

The physical operating characteristics of the reservoirs were provided by the *Operador Nacional do Sistema Elétrico* (ONS) and *Companhia Hidroelétrica do São Francisco* (CHESF). In relation to the inflows of the reservoirs for the study periods, the data of naturalized and incremental flows available in the Reservoir Monitoring System (SAR) of ANA were used.

The information about the water demands of all consumptives uses at the main channel of the São Francisco River were obtained through the registration of grants, provided by ANA (Agência Nacional de Águas, 2017c), and considered valid in 2017 (presented in the Tables A1 and A2 from Appendix A of this paper). Each water demand value was represented by fixed twelve months data series for all years of simulation. As for the demands of hydroelectric power generation, the monthly averages of historical hydroelectric power generated were used for the set of reservoirs related to the Northeast Subsystem (Sobradinho, Itaparica, Paulo Afonso Complex and Xingó) and for Três Marias, which belongs to the Southeast/Center-West Subsystem, illustrated in the Figures B1 and B2 (Appendix B).

Table 1. Operational characteristics of the reservoirs of Três Marias, Sobradinho and Itaparica.

Reservoir	Minimum Operational		Maximum Operational		Live Storage (hm^3)
	Elev. (m)	Vol. (hm^3)	Elev. (m)	Vol. (hm^3)	
Três Marias	549.2	4,250	572.5	19,528	15,278
Sobradinho	380.5	5, 447	392.5	34,116	28,669
Itaparica	299.0	7,234	304.0	10,782	3,548

Source: ANA (Agência Nacional de Águas, 2019).

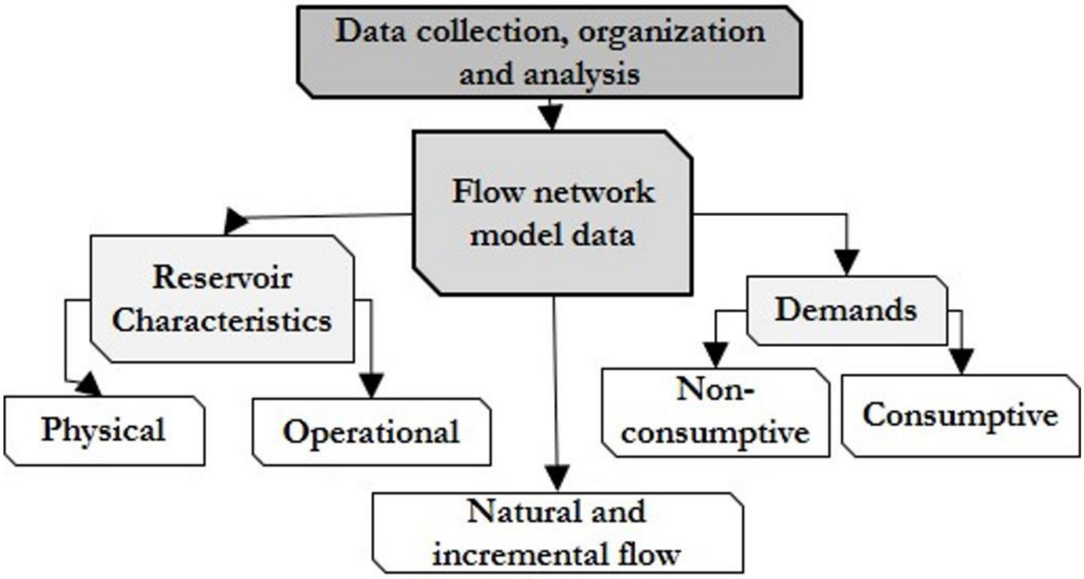

Figure 3. Description of the data acquired to perform the simulation in the flow-network model (Source: The authors).

The environmental hydrogram structured by the Ecovazão network was adopted (Medeiros et al., 2010). However, this hydrogram was adjusted by Basto (2018) for the pattern of flows of very dry years, which occurred as of 2013. Figure 4 illustrates the environmental hydrogram proposed by the Ecovazão network and then adjusted by Basto (2018).

Construction of alternative outflow scenarios

Figures 5 and 6 describe the alternative scenarios of outflows considered and their respective adopted assumptions.

Simulation and prospection of alternative outflow scenarios

The simulation was carried out using the Water Evaluation and Planning System (WEAP) flow-network model, which is capable of representing the São Francisco River water system and inserting prospective scenarios, such as different reservoir operation rules. This model is based on the water balance calculation between water supply and demand, as well as having algorithms that make it possible to establish supply preferences among users. In the periods in which the system has lower water availability, the uses with higher priority are previously served in comparison to the others. Therefore, uses with priority “1” have higher supply priority and “99” the lowest.

A sensitivity analysis of the WEAP model was carried out in order to obtain better performance regarding the representation of the operation of the reservoir complex. To this end, different priorities were assigned to serve the uses so that the outflows measured in the actual system would produce simulated storage volumes similar to the volumes observed in the São Francisco River reservoir complex.

Table 2 presents the priorities adjusted in the sensitivity analysis of the WEAP model.

With the objective of following the national law of water resources (nº 9433/1997) (Brasil, 1997), the water demands for human supply and animals feeds were discounted from the data series of inflows to the reservoirs. This approach consists of a strategy for better functioning of the WEAP model, since even the demands with priority “1” can present water deficits in some periods. Thus, the demands for human supply and animal feeds (priority water uses in situations of water scarcity) will be fully met.

Another component of the water balance calculation that should be point out is the evaporation loss. To describe the evaporation processes and the head for hydropower generation in the simulations, the WEAP model uses a cylindrical shape which represents the reservoir area, calculated by the “Volume Elevation Curve” (Water Evaluation and Planning System, 2016). For the simulation carried out, it was considered a monthly net evaporation rate for each reservoir, which is a subtraction between evaporation and precipitation on the surface area. The evaporation net from the reservoirs is presented in the Table C1 (Appendix C) of this work.

Therefore, the results of the simulations in the model submitted to three evaluations, which are presented in Figure 7.

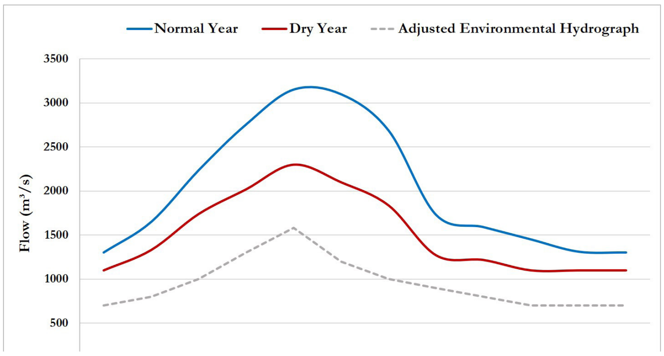

Figure 4. Environmental hydrogram structured by the Ecovazão network and environmental hydrogram adjusted for extremely dry years (Source: Medeiros et al., 2010; Basto, 2018).

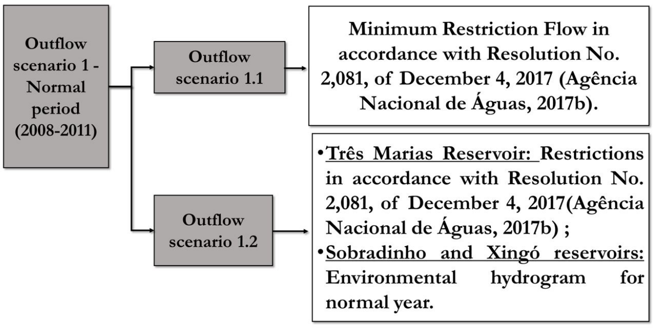

Figure 5. Assumptions adopted for the alternative outflows scenario 1 (normal period). (Source: The authors; Agência Nacional de Águas, 2017b).

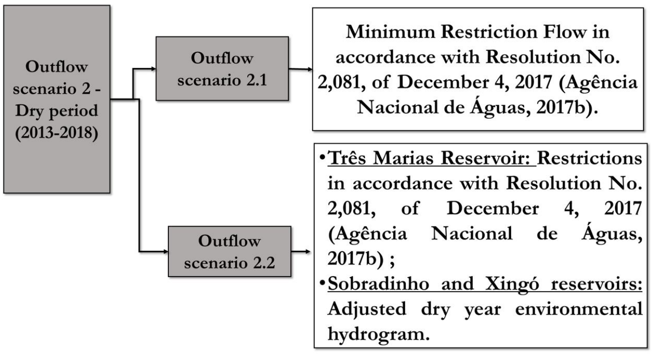

Figure 6. Assumptions adopted for the alternative outflow scenario 2 (dry period). (Source: The authors; Agência Nacional de Águas, 2017b).

In evaluation 1, the analysis consisted in verifying whether the simulated volumes meet the operating restrictions established by Resolution No. 2081, of December 4, 2017 (Agência Nacional de Águas, 2017b). In view of this, the main guidelines for the operation of the São Francisco River reservoir complex are presented in Tables 3 and 4.

As shown in Table 4, the restrictions of the Itaparica reservoir are submitted to the operating range of Sobradinho reservoir. As the Resolution does not specify a minimum volume of Itaparica, a live storage level of 10%, limit practiced by ANA for this reservoir during the period of water shortage was applied.

Another aspect considered in the analysis of the results refers to the limit of the minimum volume. The water system must operate safely to meet multiple uses, so the reservoirs must not exceed the "Restriction" operating range. Therefore, the level of live storage for the Sobradinho reservoir should be above 20% and for the Três Marias and Itaparica reservoirs it should be higher than 30%.

It is noted that the Xingó hydroelectric power plant is operated on a run-of-river system and therefore has no storage capacity. As a result, its minimum restriction flow rules are subject to the storage volume of the Sobradinho reservoir.

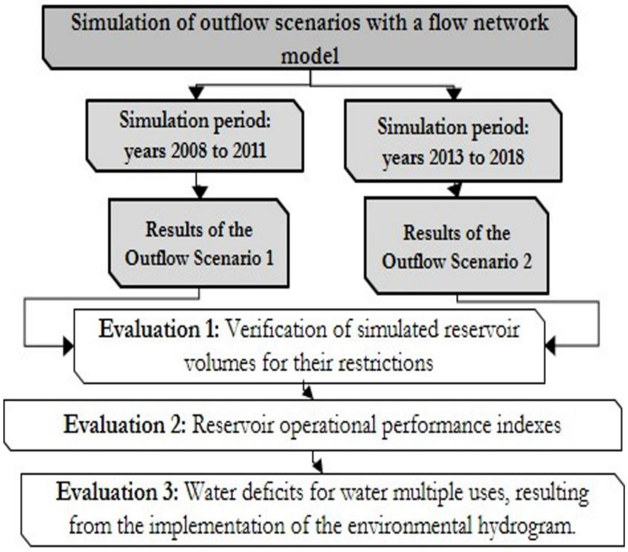

Figure 7. Evaluation of the results for the alternative outflows scenarios. (Source: The authors).

Table 2. Attendance priorities adjusted in the WEAP model by purpose of water use or operation restriction.

Purpose	Priority
Minimum Restriction Flow	1
Aquatic Ecosystem	1
Irrigation, industry, aquaculture, mining, thermoelectric and other uses	2
Storage for Três Marias reservoir	3
Storage for Sobradinho and Itaparica reservoirs	4
Hydropower generation	5

Source: The authors.

Evaluation 2 consisted of calculating operational performance indexes regarding the satisfaction of consumptive demands and hydroelectric power generation, which are: Reliability (Rel.), Vulnerability (Vul.), Resilience (Res.) and Sustainability (SI) (Hashimoto et al., 1982; Loucks, 1997). Reliability expresses the probability that a reservoir has sufficient water supply to completely satisfy the demands, while resilience measures the capacity of a system to recover after the occurrence of a supply failure. The vulnerability index measures the severity of the supply deficit and sustainability is the combination of the other performance indexes.

$$Rel = \frac{1}{K}\sum_{j=1}^{K} Z_i \tag{1}$$

"K" is the number of time steps, and "Zi" = 1 if the operation is satisfactory, "Zi" = 0 unsatisfactory operation.

$$Res = \left[\frac{1}{M_i}\sum_{j=1}^{M} d_i\right]^{-1} \tag{2}$$

"Mi" is the number of occurrences of unmet demands, "i" the demand and "di" the duration of the deficit.

$$Vul = \frac{\sum_{j=1}^{M} S_i}{\sum_{j=1}^{K} D_i} * 100 \tag{3}$$

"Si" is the total deficit volume of a given demand "i" and "Di" is the total demand volume.

$$SI_i = Rel_i \times Res_i \times \left(1 - Vul_i\right) \tag{4}$$

Adeloye et al. (2016) discussed that there are not sufficient guidelines to set thresholds for the performance indexes such as the reliability, since they are arbitrary and are not a fixed value. Campos et al. (2014), for instance, considered a threshold of 90% reliability for meeting demands without constituting a failure in the system. Therefore, this study based on the limit of 90% as reference value for the indexes reliability, resilience and sustainability. Regarding the vulnerability index, it was considered the same classification outlined by Goharian et al. (2016), who proposed the following ranges: low (0%-10.5%), medium (10,6%-15.30), medium-high (15.40%-23.70%), high (23.8-29.1), medium-extreme (29.20%-33.20%) and extreme (33.3%-40.20%).

Analysis 3 based on quantifying the water deficits for water uses, produced by the simulation of the system operation in each alternative outflow scenario, and comparing them to evaluate the

Table 3. Minimum restriction flow conditions for Três Marias and Sobradinho reservoirs, established by Resolution No. 2081, of December 4, 2017 (Agência Nacional de Águas, 2017b).

Reservoir	Operating range	Volume	Minimum Restriction Flow (m^3/s)
Três Marias	Normal	Vol. ≥ 60% L.S.	150
	Attention	30% L.S. ≤ Vol. < 60% L.S.	150
	Restriction	30% L.S.> Vol.	100
Sobradinho	Normal	Vol. ≥ 60% L.S.	800 (Sobradinho) and 1,100 (Xingó)
	Attention	20% L.S ≤ Vol. < 60% L.S.	800 (Sobradinho and Xingó)
	Restriction	20% L.S.> Vol.	700 (Sobradinho and Xingó)

impact of the operation, taking into consideration the natural river seasonality required to meet the needs of aquatic ecosystems.

RESULTS AND DISCUSSION

In the following topics the analysis results of the simulation of the São Francisco River water system, using the WEAP model were present.

Table 4. Minimum restriction flow conditions for Itaparica reservoir, established by Resolution No. 2081, of December 4, 2017 (Agência Nacional de Águas, 2017b).

Reservoir	Operating Range (Sobradinho)	Minimum storage
Itaparica	Normal or Attention	30% of the live storage
	Restriction	Not defined.

Figure 8 illustrates the network flow representation of the water system under study.

Analysis of the simulation of the reservoir operation

According to Figure D1 (Appendix D), the results of the simulated volumes for the outflow scenario 1.1 suggest that this operation promoted reservoir volumes above the "Normal" operating range. Considering Três Marias reservoir, from February 2008 to the end of the simulation, the volume of the reservoir is full, coinciding with the level of the flood control storage. As a result, throughout the period considered, this operation mode promotes the volume maximization for Três Marias reservoir. Thus, this logic of operation turns more efficient, since this structure is located in a strategic area where has a lower evaporation water loss in comparison to the other reservoirs of the system. For this

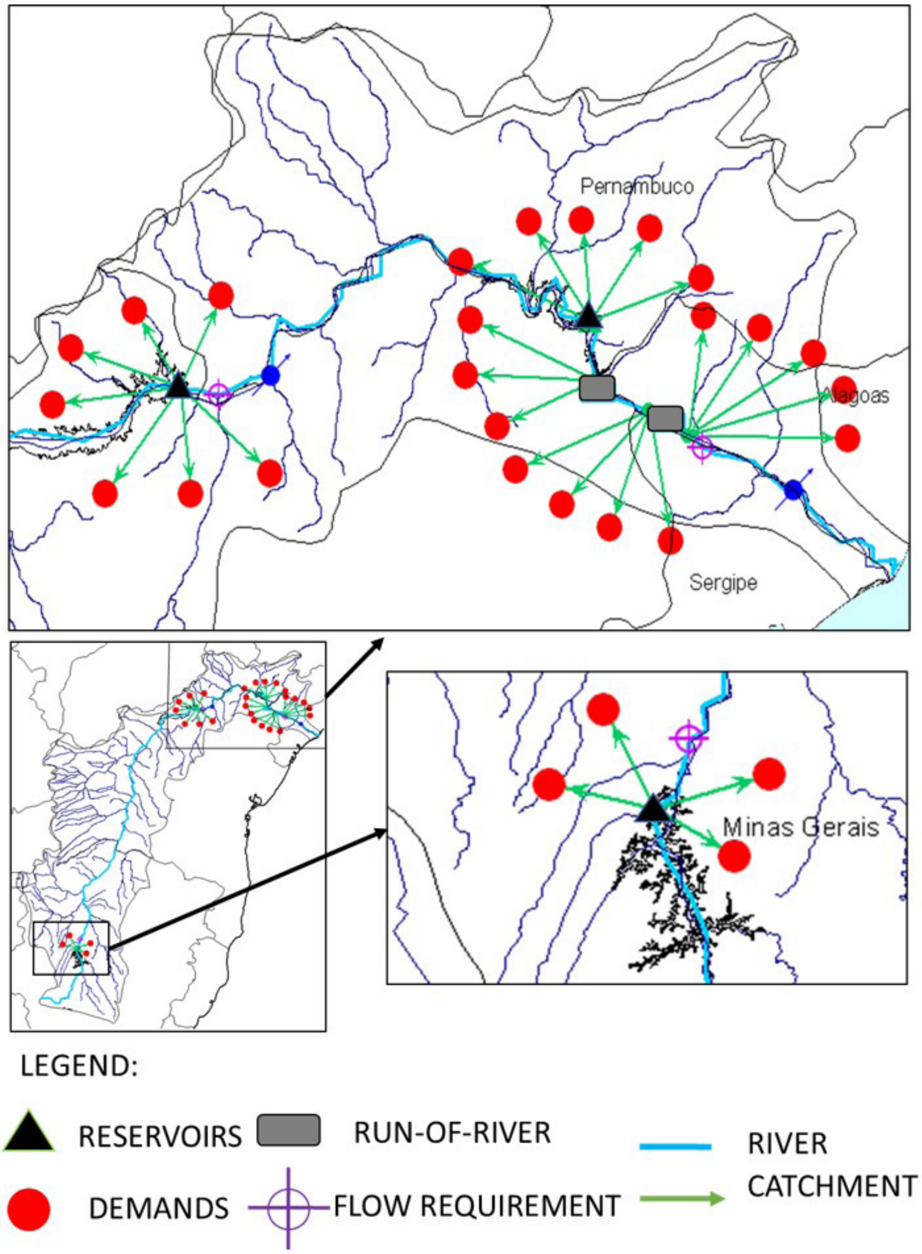

Figure 8. Structure of the São Francisco River water system in a flow network in the WEAP model.

reason, these rules not only promote more water availability for the system but also increases the security to meet the water demands and restrictions, especially for hydropower demand, since outflows with higher magnitudes are required.

In contrast, the outflow scenario 1.2 produced lower magnitude volumes for three reservoirs, exciding the "Restriction" operating range. Regarding the results for Sobradinho reservoir, the target volume was not exceeded by more than 20% of the live storage in almost the entire simulated period, especially in the months of November and December 2010, when it was 3% of the live storage.

On the case of Itaparica reservoir, the target volume for this structure is subject to the operating ranges of the Sobradinho reservoir. Consequently, the outflow scenario1.2 for the interval of the months from December 2009 to January 2010, which the operation of the Sobradinho reservoir is in the range of "attention", demonstrates the noncompliance with the target volume of 30%, with lower volume in February 2010 (9% of the live storage). As well as the other months of the simulation the target volume of 10% of the live storage was not met with a minimum volume of 4% in January 2011.

It is worth highlight that the volumes represented in the first year of simulation presented in Figure 9 (year 2007) and Figure 10 (year 2012), called "current accounts", should be disregarded since they represent the initial reference year for the calculation of the model and their results are irrelevant.

Considering the dry period (2013-2018), illustrated in Figure D2 (Appendix D), the difference between magnitudes of the simulated volumes in the outflow scenarios 2.1 and 2.2 were smaller compared to the results of the normal period (2008 - 2011). Given the results Sobradinho reservoir, for instance, the series of simulated volumes for outflow scenario 2.1 demonstrated live storage level below 20% in November 2016, September 2017 to January 2018 and in October and November 2018, with a minimum volume of 8% in November 2017. Concerning the simulated volumes produced by the outflow scenario 2.2, the series for Sobradinho reservoir was maintained for most of the simulated period with useful volume values below 20%, with a minimum magnitude of 2% in November 2017. Over the same period, the minimum simulated volume for Itaparica reached a level of 3% of the live storage.

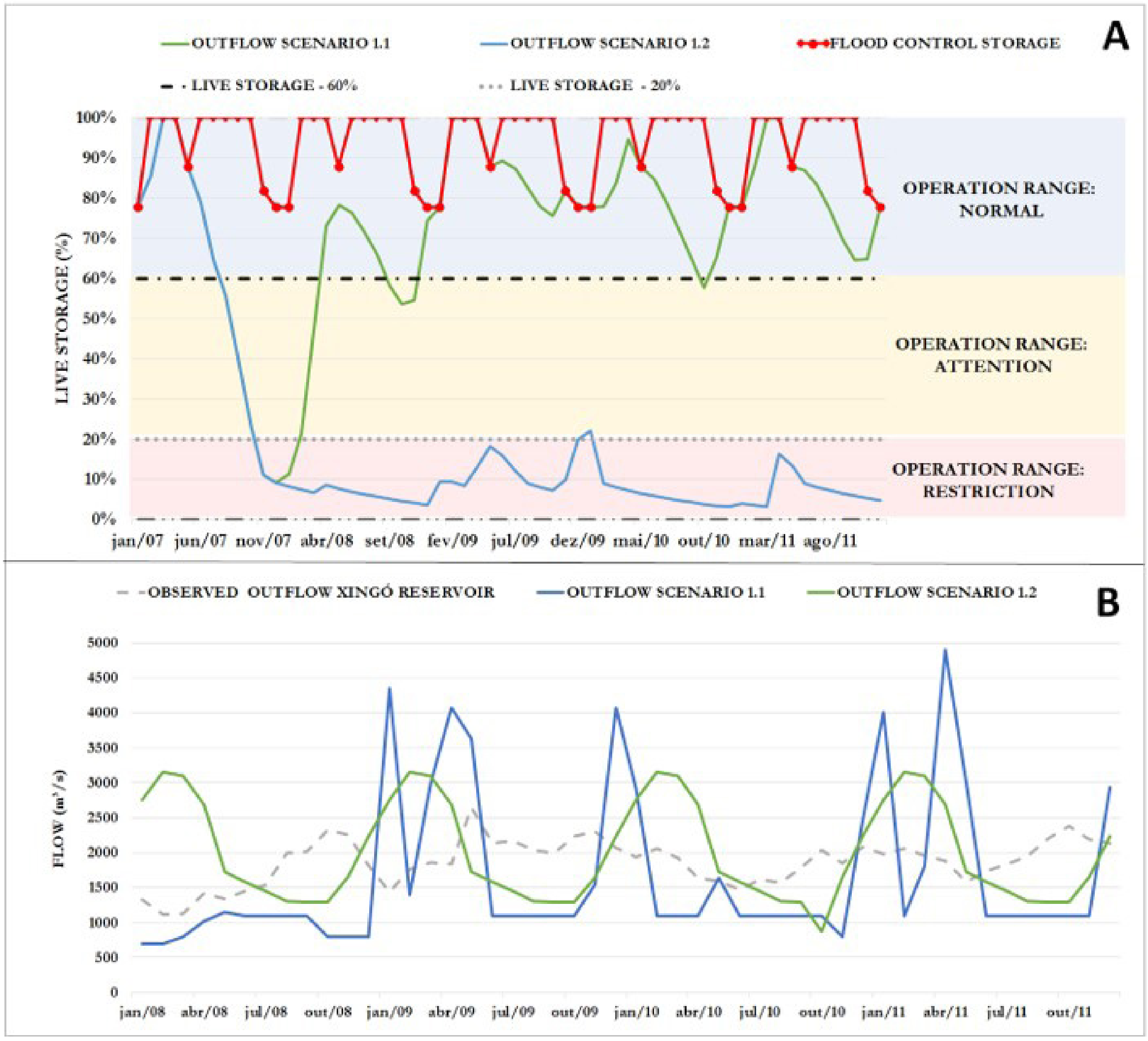

Figure 9. (A) Operating ranges and simulated volumes for the Sobradinho reservoir, period 2008 to 2011; (B) Observed and simulated flow in the downstream stretch of Xingó (Period 2008 to 2011).

Figure 10. (A) Simulated operating ranges and volumes for the Sobradinho reservoir, dry period (2013-2018); (B) Observed and simulated flows in the downstream stretch of Xingó in the dry period.

It is important to realize that due to Itaparica and Três Marias reservoirs has no bottom discharge, the inactive storage cannot be accessed, so volumes close to this level should be avoided. As a result, the non-compliance with the target volume for Itaparica reservoir it would be necessary to balance the volumes of the three reservoirs to prevent this structure from exceeding the inactive storage level.

Although all four (1.1, 1.2, 2.1 and 2.2) outflow scenarios have the same operating assumptions for the Três Marias reservoir, the flow scenarios 1.2 and 2.2 showed smaller storage volumes. This situation was a consequence of the necessary runoff with higher magnitudes than the other scenarios, since they aim to meet the downstream conditions, especially those associated with the environmental hydrogram.

In view of Sobradinho and Itaparica reservoirs, on the other hand, the difference in water availability for the volumes stored between the outflow scenarios 1.1 and 2.1 is noted. Both scenarios have the same operating assumptions, but the magnitude of the inflows for this reservoir were significantly lower in the dry period (2013 to 2018), with average naturalized flow for the stretch of the Sobradinho reservoir of approximately 1,200 m^3/s. and in the normal period (2008 to 2011) the average flow was 2,300 m^3/s, which represents a reduction of 48%.

In addition, the occurrence of lower storage volumes of the Sobradinho reservoir in 2017 in relation to the other years of the simulated period was certainly due to the inflows with lower historical values from 1931 to 2018, verified in December 2016 to April 2017 (wet months) and May to November 2017 (dry months) (Agência Nacional de Águas, 2019, 2018). Therefore, inflows with low magnitudes in the wet months cause a lower water input for the subsequent dry months, since the wet period is the season that provides the restitution of water stocks in the reservoirs.

It is worth mentioning that when performing the simulation in the WEAP model the restriction was defined so that the storage of the reservoirs did not reach the inactive storage. So, the demands were discounted to obtain water availability and avoid the reservoir reaching this level.

Briefly, given the presented results, the outflow scenarios 1.2 and 2.2 showed less security in meeting the target volumes, presenting storage volumes close to the dead volume, with more emphasis on the dry period of 2017. Thus, these results are following the statement of Sayers et al. (2016), since traditionally the meeting of environmental demand is neglected in periods when water supply is limited, as it imposes more restrictive limits on water uses.

Analysis of simulated flows in the downstream stretch of Xingó

The following figure associates the simulated storage volumes of the outflow scenarios 1.1 and 1.2 for the Sobradinho reservoir and their respective operating ranges (Figure 9A) with the simulated flows for the downstream stretch of Xingó (Figure 9B).

For the results presented for outflow scenario 1.1 Figure 9B shows the occurrence of maximum peak flows in the flow series for three years of simulation: January, April and May 2009; December 2009 and May 2010; and January and April 2010. This fact describes the flows discharged by the Sobradinho reservoir in the periods in which the level of its storage volume exceeds the level of the flood control storage, as illustrated in Figure 9A.

The months in which the outflows of the Xingó reservoir were above 1,100 m^3/s, represent the calculation made by the WEAP model for minimum outflow (established by Resolution No. 2081 of December 4, 2017) (Agência Nacional de Águas, 2017b), which relates the simulated volume of the previous month of the Sobradinho reservoir with the minimum restriction flow of the Xingó reservoir for the following month. Thus, as the Sobradinho reservoir is in the "Normal" operating range from December 2008 to September 2010, soon the outflow equal to or above 1,100 m^3/s for the Xingó reservoir occurred in January 2009 to October 2010.

However, the results of the flows simulated in the downstream section of Xingó for the outflow scenario 1.2, were non-compliance with the minimum flow in the month of October 2010 with a deficit of 423 m^3/s.

When comparing the results of the scenarios under study, it can be seen that the evolution of flows in the outflow scenario 1.1 presents the occurrence of maximum flow peaks without a regular pattern between the years and with abruptly way, since it does not present outflows with magnitudes corresponding to the transition months of the dry and normal hydrological periods.

On the other hand, the evolution of flows described by the environmental hydrogram (outflow scenario 1.2) is a gradual pattern, with maximum flows pattern in the months of the wet period from February to March.

Figure 10 illustrates the results of the simulations for the downstream stretch of Xingó, for the dry period (2013-2018).

Although the minimum flow restriction has priority 1 in this simulation, in situations where water availability is insufficient, the water balance calculation performed by the WEAP model discounts the flow required by this restriction. This occurred not only because of the magnitudes of the simulated outflow, but also because of the low inflows and levels of the Três Marias, Sobradinho and Itaparica reservoirs near the inactive storage level. This fact was reflected in the non-fulfillment of this restriction and damages to the satisfaction of the water demands.

While the assumptions applied in the simulation of these scenarios do not describe outflows with a constant minimum flow (which is detrimental to the maintenance of aquatic ecosystems) they take into account a range of different outflows associated only with the fluctuation of reservoir water volumes, without respecting the natural variability of river flows and complexity of aquatic ecosystems requirements, described by Bunn & Arthington (2002). The outflow scenario 1.1 for example, although the simulated outflows provide for floods in wet months, the flow series does not show a seasonal pattern. Therefore, the operating logic presented in outflow scenarios 1.1 and 2.1 demonstrated a disadvantageous operation under the environmental aspect, since seasonality and predictability are one of the main parameters that interfere with the health of aquatic ecosystems.

In contrast, the outflow scenarios 1.2 and 2.2 proved unsustainable when considering meeting environmental demand. In particular, the outflow scenario 2.2 presented major deficits in the dry months of 2017.

Analysis of the meeting of consumptive demands

Table 5 illustrates the performance indexes regarding the meeting of water demands for consumptive uses (with the exception of the human supply and animal feed, which have already been previously met), considering the outflow scenarios under study.

According to Table 5, the outflow scenarios 1.2 and 2.2, which consider the meeting of environmental demand, did not obtain maximum values for the reliability, resilience and sustainability indices and minimum values for the vulnerability index. It should be noted that the calculation was performed from the monthly attendance throughout the simulation period, considering each category of demand belonging to the system.

Among the results for the outflow scenario 1.2 and 2.2, although the reliability indexes not presented maximum values, these are above of the threshold of 90%, which means the 10%

Table 5. Average performance indices to meet consumptive uses.

Outflows scenarios	Consumptive uses	Rel.	Res.	Vul.	Sust.
1.1 and 2.1	Irrigation	100%	100%	0%	100%
	Aquaculture	100%	100%	0%	100%
	Industry	100%	100%	0%	100%
	Mining	100%	100%	0%	100%
	Thermoelectric	100%	100%	0%	100%
	Other	100%	100%	0%	100%
1.2	Irrigation	97%	58%	7%	52%
	Aquaculture	97%	58%	7%	53%
	Industry	98%	83%	4%	78%
	Mining	96%	50%	7%	45%
	Thermoelectric	96%	50%	7%	45%
	Other	98%	70%	4%	66%
2.2	Irrigation	93%	56%	9%	47%
	Aquaculture	93%	44%	8%	38%
	Industry	96%	78%	4%	72%
	Mining	91%	67%	9%	55%
	Thermoelectric	91%	33%	9%	28%
	Other	94%	56%	6%	49%

of total demand non meeting demand is not significant to be considered as a fail of the system operation.

With regard to the resilience index, only the industrial use obtained probability above 80% (outflow scenario 1.2) and 70% (outflow scenario 2.2). It is observed that the higher this index is the greater the capacity of a system to recover from a failure, therefore as the indexes reached values below the limit of resilience index (90%), this represents the occurrence of a long period of water shortage and a slow recovery capacity of the system in relation to the deficit.

The vulnerability index, on the other hand, measures the extent of a failure. The smaller this index is the more robust the system will be. As a result, the use of irrigation, aquaculture, mining and thermoelectric power plants proved to be more vulnerable in both scenarios, reaching rates between 7% and 9%. However, these results were classified as a low vulnerability level, with values lower than the threshold of 10.5%.

For the sustainability index, it relates the results of reliability, resilience and vulnerability. Only the use of water for industry reached a value above 70% for the sustainability index, reflecting the results of the other indexes.

The main reason for the low values of the sustainability index in the outflow scenario 2.2 in particular for aquaculture (38%) and thermoelectric (28%) uses, was the occurrence of a long period not meeting demands (July to November 2017), which promoted deficits with considerable magnitude in five consecutive months. This produced indices with unsatisfactory values for resilience and consequently sustainability.

Therefore, the results of the simulations scenarios 1.1 and 2.1 showed indexes with better performance in terms of meeting the multiple uses, which reached sustainability indexes with values equal to 100%. This reveals systems with reliable operations that satisfy consumptive demands with resilience to recovery from service failures and little vulnerability.

Figures 11 and 12 illustrate the monthly meeting of consumptive demands for scenarios 1.2 and 2.2. It is worth noting that there were no deficits for these uses in outflow scenarios 1.1 and 2.1.

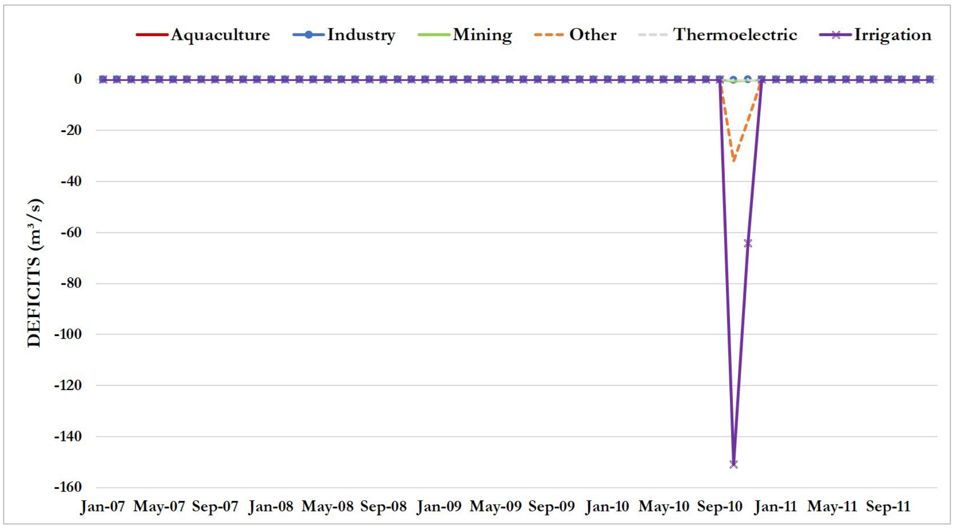

Figure 11. Water deficits for consumptive uses (outflow scenario 1.2).

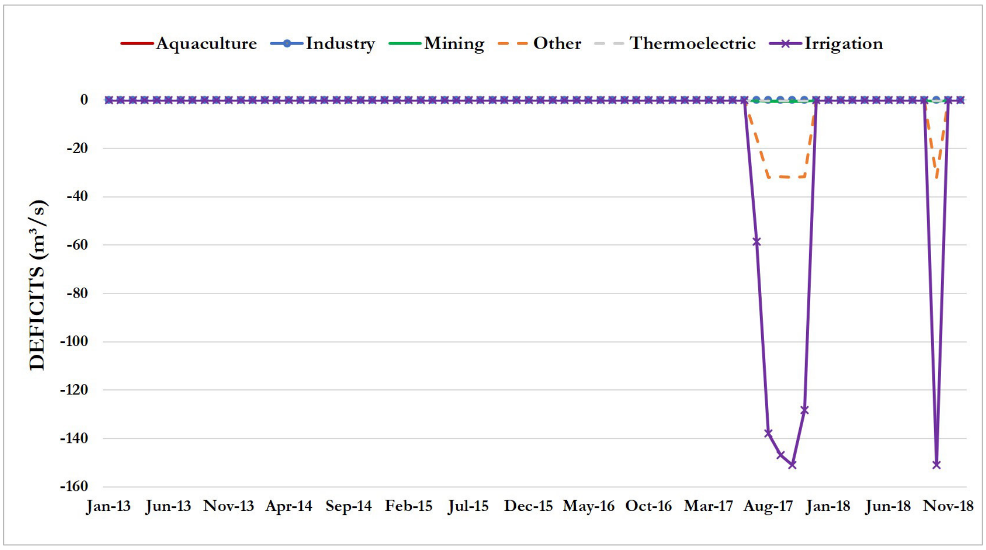

Figure 12. Water deficits for consumptive uses (outflow scenario 2.2).

According to Figure 11 it is observed that the outflow scenario 1.2 obtained deficits in meeting the consumptive uses for the months October and November 2010 and for the irrigation sector, the month with the largest deficit was October (151 m^3/s). The other consumptive uses, however, the deficits with greater importance were a group of uses called "others" (corresponding to the transposition projects and small uses that are not included in the other categories) and mining, an approximate flow of 33 m^3/s and 0.5 m^3/s in the month of October.

In terms of meeting the consumptive uses in the outflow scenario 2.2 presented in Figure 12 there were water deficits in the two-year study period. In 2017, the deficits occurred between July and November and in 2018 there was a deficit in October. Similar to the results of the outflow scenario 1.2 the sector that presented the greatest deficit was the irrigation with the greatest magnitude in October 2017 and 2018, this represents a flow rate of 151 m^3/s. Next, the consumptive uses with greater losses were the "other" and mining sectors with greater deficits in the months of August to November 2017 and October 2018 which corresponds to a monthly flow of 32 m^3/s (sector "others") and 0.5 m^3/s (mining).

It is worth noting that the percentage of service admitted for the demands of each use was the same (all with priority 2), thus the importance of deficits for irrigation was greater due to the larger magnitude of their demands in relation to other uses.

Concerning the water deficits for the use of irrigation (most impacted use) per stretch, according to Figures 13 and 14, the stretches with greater deficits are included downstream of the reservoirs from Três Marias to Sobradinho (stretch 2) and the stretch downstream of the reservoir Sobradinho to Itaparica (stretch 3). In the case of outflow scenario 1.2 the losses for irrigation in stretch 2 with higher magnitude occurred in the month of October 2010, with a total of 94 m^3/s and for section 3 it was 41 m^3/s for the same month. For the outflow scenario 2.2 the period with the largest deficit for this sector in section 2 was 97 m^3/s (September 2017) and in section 3 was 41 m^3/s (October and November 2017 and October 2018).

The distribution of water deficits in the WEAP model by stretch of river did not differentiate priorities for these demands, so occurred (as in the previous analysis) due to the greater magnitude of flows granted in these stretches, plus part of these flows come from projects with large irrigated areas that demand extensive amounts of water, such as the Jaíba and Senador Nilo Coelho projects.

Analysis of the meeting of hydroelectric energy demands

Table 6 illustrates the performance indexes for meeting the hydroelectric energy demands for the Northeast Subsystem.

In contrast to the consumptive uses, the sustainability indexes for hydroelectric energy demand were below 6% in all the outflow scenarios contemplated in this study. The reasons that led to these unsatisfactory values were the occurrence of large deficits over long periods and consecutive months.

Figures 15 and 16 illustrate the water deficits for the hydroelectric sector.

Table 6. Performance indices to meet the demands of hydroelectric energy (Northeast Subsystem).

Outflow scenarios	Rel. %	Res. %	Vul. %	Sust. %
1.1	23	16	32	3
1.2	38	13	18	4
2.1	24	4	26	1
2.2	40	16	21	5

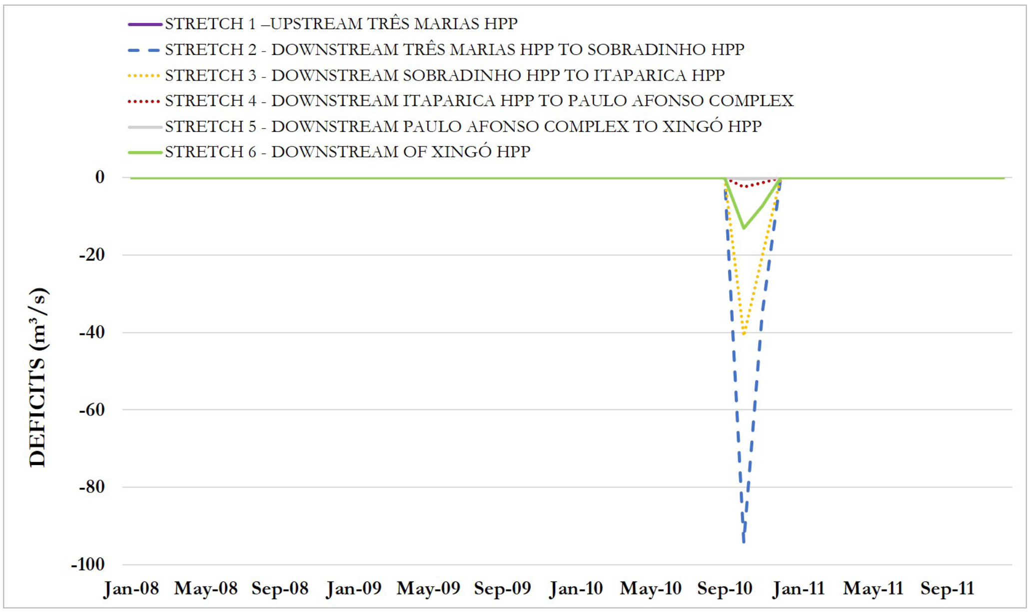

Figure 13. Water deficits for the use of irrigation by stretch (outflow scenario 1.2).

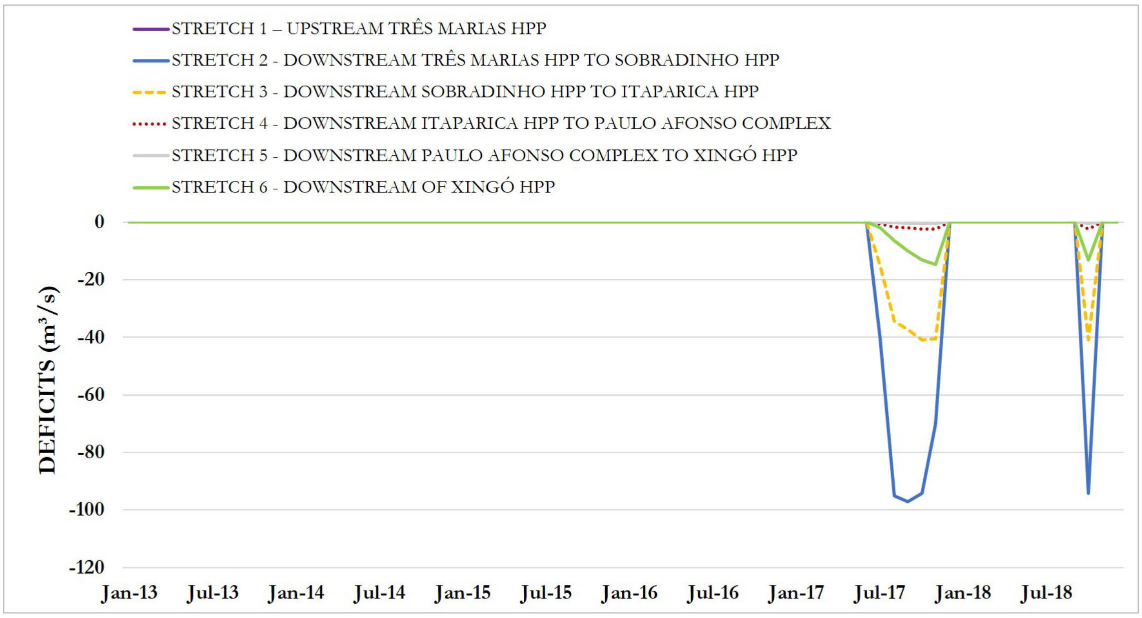

Figure 14. Water deficits for the use of irrigation by stretch (outflow scenario 2.2).

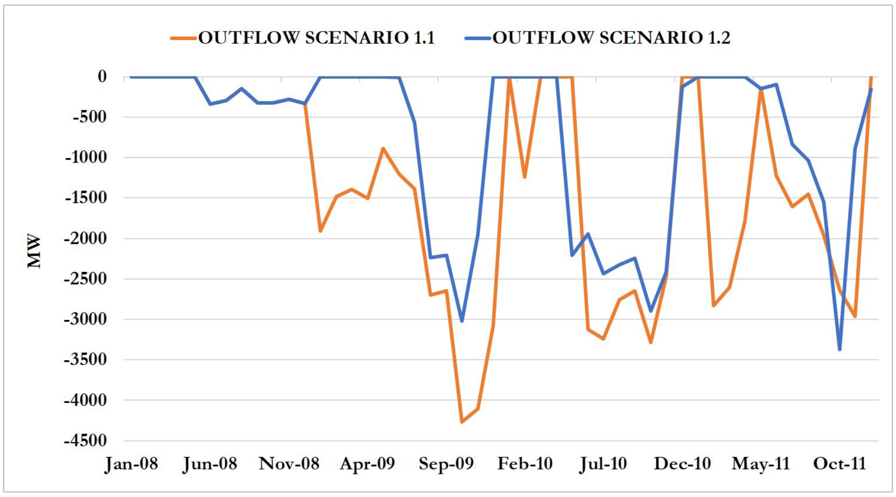

Figure 15. Deficits for hydroelectric generation demand of the Northeast Subsystem for the period 2008 to 2011, in Megawatt (MW).

Comparing the results of the simulations for hydroelectric power generation of outflow scenario 1.1 with 1.2 proved to be less reliable to meet this demand (a probability of only 23% guaranteed supply) as in the majority of the months in the simulated period there were deficits, with demand being met in the months of January, March, April and May 2009, December and January 2010 and April, May and December 2011. In the case of the outflow scenario 1.2 even though this mode of operation had a higher reliability index than the previous scenario (38% guarantee of supply), there were supply deficits in all simulation years, especially in months considered dry (May to November). Both scenarios presented a low recovery capacity for supply failure (probabilities for the resilience index below 20%) and vulnerable, although the proportion between unmet and required demand is lower for the outflow scenario 1.2, with an index of 18%, classified as a medium-high vulnerability level. As for the outflow scenario 1.1 the vulnerability index of 32% presented a classification of medium-extreme level.

The one of reason that promoted the deficits were, certainly, the assumption of lower priority to meet this demand in relation to other uses and reservoir storage, which was assumed in the stage of sensitivity analysis of the WEAP model. In addition, in the case of hydroelectric power generation the greater the outflow the greater the electric power produced. Contrastingly the simulated flow in the downstream stretch of Xingó with the outflows observed for this reservoir, presented in Figure 9B showed that despite the minimum flow restriction for this period was 1,300 m^3/s (Agência Nacional de Águas, 2013), in some months the outflows exceed this magnitude. Considering the outflow scenario 1.1 the simulated outflows obeyed the minimum flow restrictions established by Resolution 2081/2017 (Agência Nacional

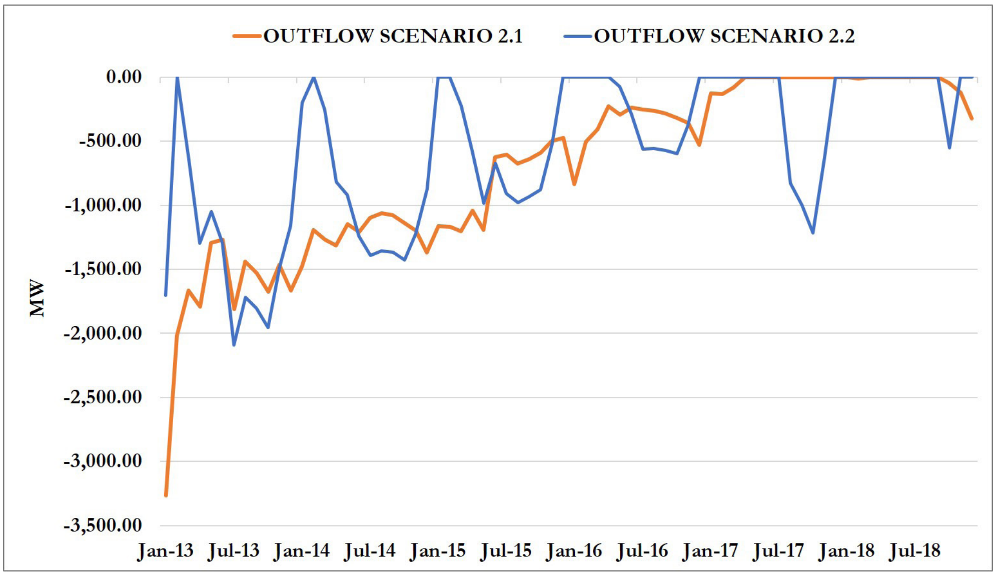

Figure 16. Deficits for hydroelectric generation demand of the Northeast Subsystem for the period 2013 to 2018, in Megawatt (MW).

de Águas, 2017b), in which the outflows varied from 700 m^3/s to 1.100 m^3/s, with the exception of the months of maximum peak flows discussed in the previous topic. Thus, in most of this period, the simulated outflows in the outflow scenario 1.1 were lower than those observed in the real system and, therefore, the hydroelectric power generation was lower in this scenario which represented deficits to satisfy this demand. This same condition occurred in the outflow scenario 1.2 where the failures occurred during the months of lower magnitude of the environmental hydrogram, with an average flow of 1,500 m^3/s and values below the observed outflows.

Given that the simulation for the dry period (2013 to 2018), the results for the outflow scenario 2.1 presented operating performance indexes lower than the outflow scenario 2.2, with a reliability index to meet demand with a probability lower than 30%, resilience to recovery from service failures of 4%. These unsatisfactory results were due to service deficits in most of the simulated period, in the range of January 2013 to March 2017. Although the simulation for the outflow scenario 2.1 presented a sustainability index of 1%, it fully met the demand for hydroelectric power in the period from April 2017 to September 2018.

In relation to the outflow scenario 2.2 the operating performance indexes also presented unsatisfactory probabilities with a sustainability index of 5% and a guarantee of meeting demands of 40%. There was a deficit in almost every month of the simulated period, especially from August to November 2017 and October 2018, when the simulation showed a failure to meet the flow required for environmental demand.

Based on the simulated period for the outflow scenarios 2.1 and 2.2, it is noted that the results showed lower water deficits to meet the hydroelectric demand in 2017 and 2018. This occurred due to the reduction of hydroelectric power production in the real system and consequently a lower demand required for hydroelectric power generation.

Comparing the average monthly hydroelectric power generated by the Northeast Subsystem in 2017 (1,879 Mwmed) to the monthly average generated in 2014 (3,411 Mwmed), there was a 45% reduction in production (Operador Nacional do Sistema Elétrico, 2019). This occurred as a result of water scarcity in the basin where the flexibility of minimum flows impacted on the reduction of hydroelectric power generation. The month of October 2017when the outflows to the Sobradinho and Xingó reservoirs were 550 m^3/s, the energy installed in the system represented only 1,550 MW, about 15% of the total energy of the Northeast subsystem (Operador Nacional do Sistema Elétrico, 2018a, 2019). This situation led to the expansion of wind power generation to subsidize the supply for demand required by this sector. On May 28th 2018, for example, wind generation accounted for 58.3% of all electric load generated in the Northeast Subsystem, with hydraulics accounting for only 19.2% (Operador Nacional do Sistema Elétrico, 2018b). On the national scene, the Northeast Subsystem was responsible for 80% of the installed capacity of the wind power plants in operation at SIN in 2017 (Operador Nacional do Sistema Elétrico, 2017).

In summary, taking into consideration the results of indexes discussed as low values, this described the trade-off between hydroelectric demands and reservoirs restrictions. Under this perspective, to reach a better system performance to meet consumptive uses, storage volume goals and environmental hydrogram requirements, it was necessary to minimize the outflow magnitudes in some periods and, consequently, the hydroelectric production was reduced. Thus, it was not possible to get performance indexes with high values for all uses simultaneously.

Despite the support provided by wind energy generation to cover the deficit of hydroelectric energy production of the Northeast Subsystem in the period of water scarcity, this energy source has a variable and intermittent behavior because it depends on meteorological conditions, thus, part of the energy produced is also supplied by thermoelectric, solar plants and energy exchanges from other subsystems belonging to the SIN (Operador Nacional do Sistema Elétrico, 2017).

Furthermore, the advantage of electric power generation is the possibility of performing compensations among other energy sources. When comparing the presented simulation results, none of the scenarios under study proved to be favorable in meeting the demand of this sector. Thereby, the impact of the operation of the reservoirs for hydroelectricity use can be reduced if there is the possibility of supporting the electric energy generated through other sources of production.

CONCLUSION

This study contributed to the evaluation of a reservoir management decision-making process established by stakeholders, which involved emergency actions to increase the water security of this system during periods of scarcity. The adoption of operating strategies for the São Francisco River water system was an effective decision to maximize the water storage of reservoirs and mitigate the effects of water scarcity resulting from climate change. However, this approach has not proved efficient from the environmental aspect, since this practice was not developed based on the seasonality and predictability of the natural flow regime. Consequently, the current rules only meet anthropogenic uses, which differ from the guidelines established in the Sustainable Development Goals (United Nations, 2017). Considering this deficiency, this work also presented an assessment of the effects on meeting multiple uses of an alternative mode of operation, including an environmental hydrogram.

From this perspective, the present study evaluated the effects of adopting an outflow regime for the São Francisco River reservoir system, which considers the demands of the aquatic ecosystem in the current guidelines for meeting the demands of multiple water uses, according to Resolution 2081/2017 of ANA (Agência Nacional de Águas, 2017b).

The outflow scenarios 1.1- normal period (2008-2011) and 2.1- dry period (2013-2018) that consider the rules established by Resolution 2081/17 demonstrated that this operating logic presents greater security in maintaining the volume of the reservoirs in the operating ranges above the minimum range of “restriction” and that it was possible to meet the water demands of consumptive uses. As for the demands of non-consumptive uses, this logic of outflow operation showed deficits in meeting the demands of hydroelectric power production, which highlights the need for compensation from other sources of energy generation. Additionally, the demand for the maintenance of aquatic ecosystems was verified in the downstream stretch of Xingó and the outflow regime showed the absence of seasonality and predictability to meet the needs of the environment.

Considering the outflow scenarios 1.2- normal period (2008-2011) and 2.2- dry period (2013-2018), which present the logic of outflow operation according to the seasonality described in the proposed environmental hydrogram. In both scenarios it is possible to observe that there is no water security to maintain the volumes of the reservoirs full, even in a situation with greater water availability, as is the case of the years of the wet period from 2008 to 2011. Meeting the demand of river ecosystems, based on the proposed environmental hydrogram proved to be unsustainable since in some periods the reservoir levels were close to the inactive storage level and showed deficits in meeting the demands of multiple uses, including the aquatic ecosystem.

The maintenance of the reservoir volumes is an essential component to ensure that the current and future demands of this water system are met, not only to satisfy human uses, but because water availability is also required to meet environmental demand. The environmental hydrogram proposed by Ecovazão network was developed through the holistic methodology BBM (*Building Block Methodology*) (King et al., 2000) and, in its structuring process, was based essentially on the hydro climatological behavior of the lower course of the São Francisco River, without any consideration of the impact of the operation suggested on the storage volumes of the reservoirs.

In view of the results presented by the outflow scenarios 1.2 and 2.2, it is recommended that the environmental hydrogram proposed for the lower course of the São Francisco River be re-evaluated. One possibility would be to incorporate into the development methodology of the environmental hydrogram a study that associates the maintenance of reservoir storage volumes with the preservation of the flow patterns of the natural river regime such as seasonality and predictability, among others (Bunn & Arthington, 2002).

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Authors contributions

Isabela Dantas Reis Gonçalves Basto: Flow-network model simulation, data and results analysis;

Andrea Sousa Fontes: Support in the analysis of results and co-supervision of the research;

Yvonilde Dantas Pinto Medeiros: Definition of the study methodology, support in the analysis of the results and supervision of the research.

Appendix A. Demands of the main channel of the São Francisco River.

Table A1. Demands of the main channel of the São Francisco River - stretch from the source to the Itaparica reservoir (Authors adaptation Agência Nacional de Águas, 2017c).

Month	Demands (m^3/s)																				
	Stretch 1 – source to Três Marias HPP						Stretch 2 -downstream Três Marias HPP to Sobradinho HPP								Stretch 3 - downstream Sobradinho HPP to Itaparica HPP						
	Human supply	Aqua.	Animal feed	Ind.	Irrig.	Other*	Human supply	Aqua.	Animal feed	Ind.	Irrig.	Min.	Term.	Other*	Human supply	Aqua.	Animal feed	Ind.	Irrig.	Min.	Other*
Jan	0.12	0.04	0.01	0.43	2.44	0.0001	3.21	0.02	0.01	0.2	97.5	0.52	0.14	0.13	3.60	0.08	0.011	0.1	46.13	0.02	26.42
Feb	0.12	0.04	0.01	0.44	2.58	0	3.21	0.02	0.01	0.2	91.9	0.52	0.14	0.13	3.58	0.08	0.011	0.1	42.05	0.02	26.42
Mar	0.12	0.04	0.01	0.43	3.47	0	3.21	0.01	0.01	0.2	91.5	0.52	0.14	0.13	3.58	0.08	0.011	0.1	42.47	0.02	26.42
Apr	0.12	0.04	0.01	0.44	5.08	0	3.21	0.02	0.01	0.2	104.6	0.52	0.14	0.13	3.58	0.08	0.011	0.1	41.69	0.02	26.42
May	0.12	0.04	0.01	0.44	5.00	0	3.21	0.02	0.01	0.2	113.6	0.52	0.14	0.13	3.59	0.08	0.011	0.1	41.99	0.02	26.42
Jun	0.12	0.04	0.01	0.43	4.43	0	3.21	0.02	0.01	0.2	100.5	0.52	0.14	0.13	3.59	0.08	0.011	0.1	41.02	0.02	26.42
Jul	0.12	0.04	0.01	0.44	5.00	0	3.21	0.02	0.01	0.2	105	0.52	0.14	0.13	3.59	0.08	0.011	0.1	39.32	0.02	26.42
Aug	0.12	0.04	0.01	0.43	6.45	0	3.21	0.02	0.01	0.2	120.6	0.52	0.14	0.13	3.60	0.08	0.011	0.1	43.62	0.02	26.42
Sep	0.12	0.04	0.01	0.44	5.65	0	3.21	0.02	0.01	0.2	123.3	0.52	0.14	0.13	3.61	0.08	0.011	0.1	47.28	0.02	26.42
Oct	0.12	0.04	0.01	0.01	4.43	0	3.21	0.02	0.01	0.2	119.4	0.52	0.14	0.13	3.61	0.08	0.011	0.2	51.96	0.02	26.42
Nov	0.12	0.04	0.01	0.01	3.14	0	3.21	0.02	0.01	0.2	88.9	0.51	0.14	0.13	3.61	0.08	0.011	0.1	51.48	0.02	26.42
Dec	0.12	0.04	0.01	0.01	1.52	0	3.21	0.02	0.01	0.2	85.9	0.51	0.14	0.13	3.60	0.08	0.011	0.1	50.24	0.02	26.42

*Transposition projects and small water uses (Agência Nacional de Águas, 2017c).

Table A2. Demands of the main channel of the São Francisco River - downstream section of the Itaparica reservoir until downstream of the Xingó reservoir (Authors adaptation Agência Nacional de Águas, 2017c).

Month	Demands (m^3/s)																
	Stretch 4 - downstream Itaparica HPP to Paulo Afonso Complex						Stretch 5 -downstream Paulo Afonso Complex to Xingó HPP				Stretch 6 - downstream of Xingó HPP						
	Human supply	Aqua.	Des. Animal	Ind.	Irrig.	Other*	Human supply	Ind.	Irrig.	Other*	Human supply.	Aqua.	Animal feed	Ind.	Irrig.	Term.	Other*
Jan	3.25	1.65	0.0003	0.0028	2.83	0.01	0.69	0.01	0.41	0.0019	6.59	0.04	0.001	0.01	16.85	0.47	0.02
Feb	3.25	1.65	0.0003	0.0028	2.54	0.01	0.69	0.01	0.39	0.0019	6.59	0.04	0.001	0.01	14.31	0.47	0.02
Mar	3.25	1.65	0.0003	0.0028	2.37	0.01	0.69	0.01	0.36	0.0019	6.59	0.04	0.001	0.01	11.68	0.47	0.02
Apr	3.25	1.65	0.0003	0.0028	2.13	0.01	0.69	0.01	0.32	0.0019	6.59	0.03	0.001	0.01	8.15	0.47	0.02
May	3.25	1.65	0.0003	0.0028	1.74	0.01	0.69	0.01	0.24	0.0019	6.59	0.03	0.001	0.01	5.81	0.47	0.02
Jun	3.25	1.65	0.0003	0.0028	1.49	0.01	0.69	0.01	0.2	0.0019	6.59	0.01	0.001	0.01	5.06	0.47	0.02
Jul	3.25	1.65	0.0003	0.0028	1.62	0.01	0.69	0.01	0.22	0.0019	6.59	0.01	0.001	0.01	5.41	0.47	0.02
Aug	3.25	1.65	0.0003	0.0028	2.07	0.01	0.69	0.01	0.33	0.0019	6.59	0.01	0.001	0.01	8.23	0.47	0.02
Sep	3.25	1.65	0.0003	0.0028	2.55	0.01	0.69	0.01	0.42	0.0019	6.59	0.03	0.001	0.01	12.68	0.47	0.02
Oct	3.25	1.65	0.0003	0.0028	3.04	0.01	0.69	0.01	0.46	0.0019	6.59	0.04	0.001	0.01	16.58	0.47	0.02
Nov	3.25	1.65	0.0003	0.0028	3.16	0.01	0.69	0.01	0.42	0.0019	6.59	0.04	0.001	0.01	18.71	0.47	0.02
Dec	3.25	1.65	0.0003	0.0028	2.91	0.01	0.69	0.01	0.4	0.0019	6.59	0.04	0.001	0.01	18.21	0.47	0.02

*Transposition projects and small water uses (Agência Nacional de Águas, 2017c).

Appendix B. Hydroelectric power.

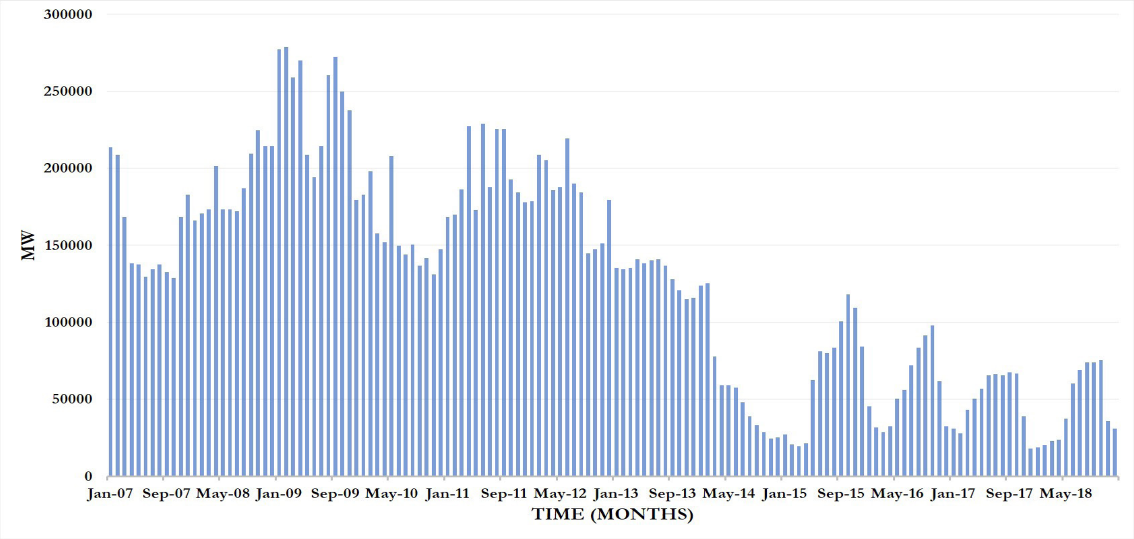

Figure B1. Hydroelectric power generated by Três Marias Reservoir (MW). Source: ONS (Authors adaptation Operador Nacional do Sistema Elétrico, 2019).

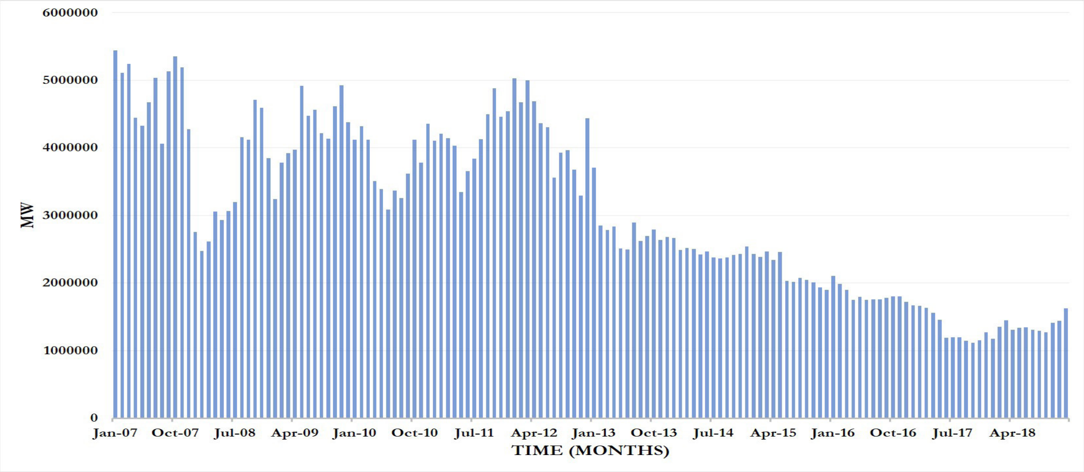

Figure B2. Hydroelectric power generated by Northeast Subsystem (MW). Source: ONS (Authors adaptation Operador Nacional do Sistema Elétrico, 2019).

Appendix C. Reservoir's evaporation.

Table C1. Reservoir's net evaporation (Authors adaptation Operador Nacional do Sistema Elétrico, 2004).

Month	Três Marias	Sobradinho	Itaparica
January	-1	171	163
February	-2	109	88
March	28	61	47
April	47	56	35
May	61	108	55
June	61	104	41
July	58	165	81
August	49	203	138
September	49	234	190
October	35	267	227
November	21	245	235
December	22	223	202

Appendix D. Simulated and observed reservoirs volumes.

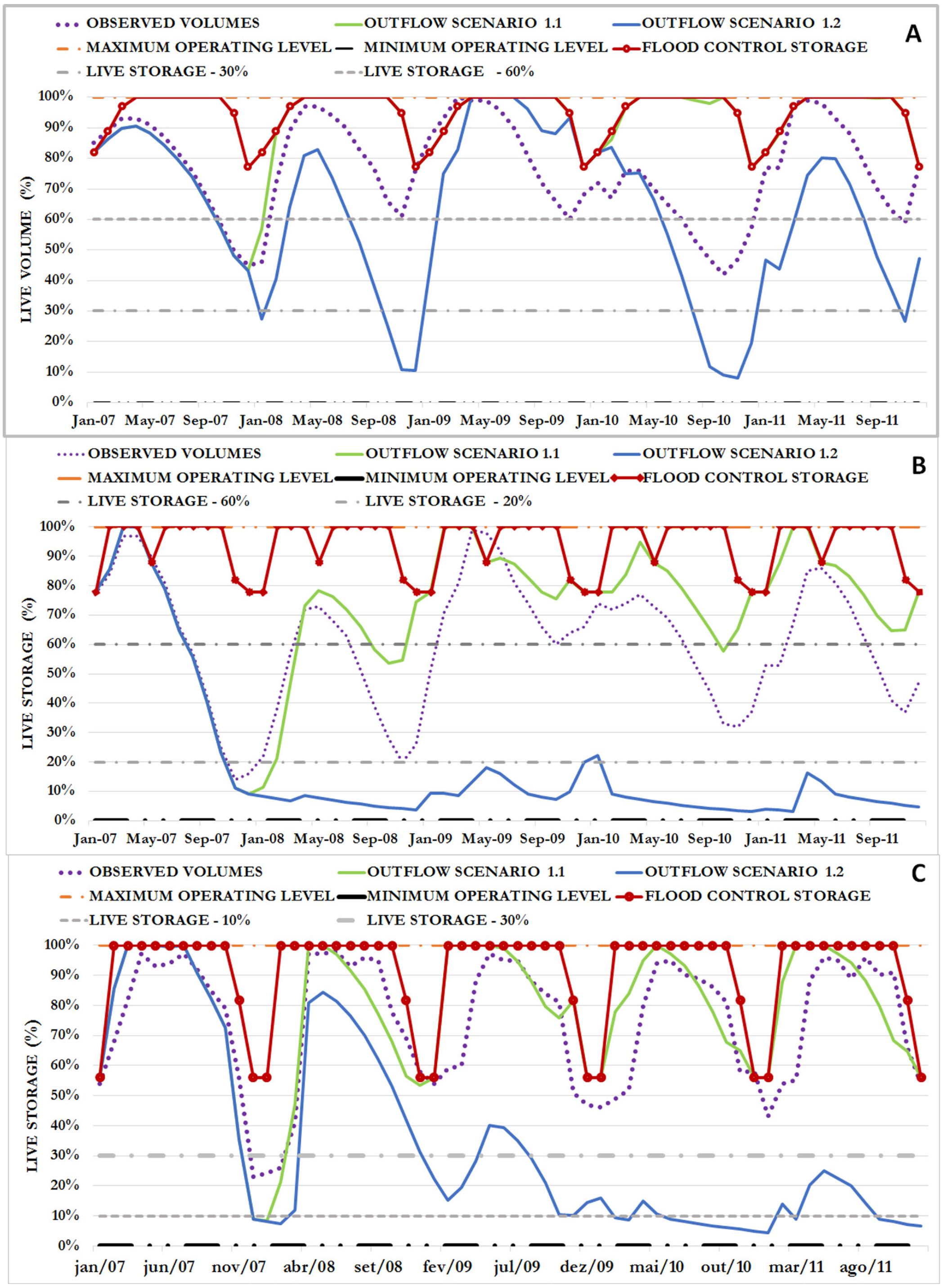

Figure D1. Simulated and observed volumes for Três Marias (A), Sobradinho (B) and Itaparica (C) reservoirs, for period 2008 to 2011.

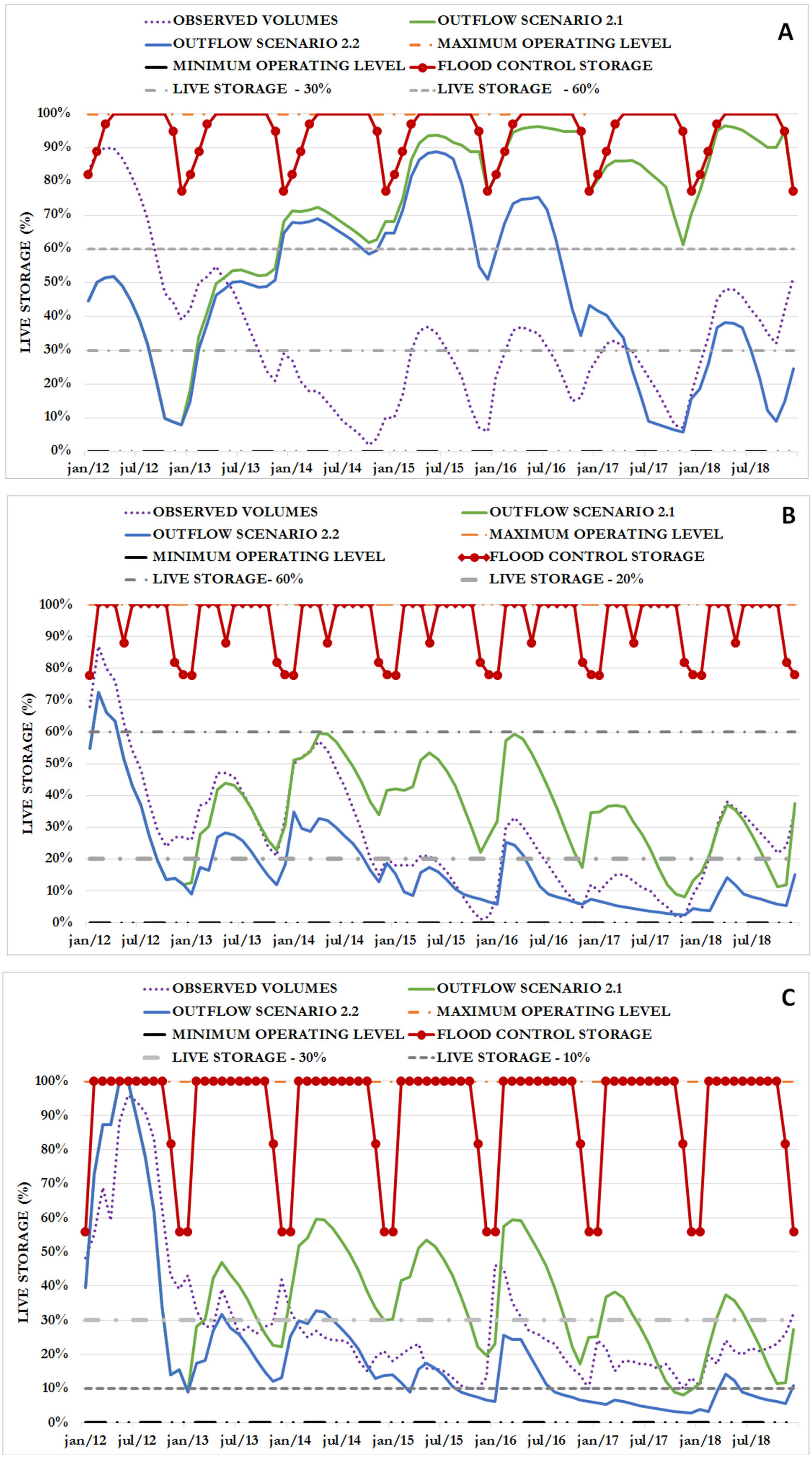

Figure D2. Simulated and observed volumes for Três Marias (A), Sobradinho (B) and Itaparica (C) reservoirs, for period 2013 to 2018.