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Cenários de alocação de água para abastecimento público e irrigação no projeto de integração do Rio São Francisco

Water allocation scenarios for public supply and irrigated agriculture in the São Francisco River integration project

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RESUMO: Para minimizar os problemas derivados da escassez hídrica no semiárido nordestino, vem sendo desenvolvido o Projeto de Integração do Rio São Francisco (PISF), transferindo águas do rio São Francisco para outras bacias nos estados de Pernambuco, Ceará, Rio Grande do Norte e Paraíba. A gestão sustentável dessas águas será primordial para garantia dos seus usos. Para tal, esta pesquisa teve como objetivo avaliar cenários de alocação de água para o abastecimento público e agricultura irrigada, com intuito de auxiliar a gestão dos recursos hídricos e a manutenção desses usos no Alto Curso do rio Paraíba (PB), Eixo Leste do PISF. A avaliação dos usos múltiplos se deu por meio da análise das outorgas emitidas para os reservatórios Poções e Epitácio Pessoa, em 2019. Cenários de alocação de água foram realizados considerando presença e ausência das águas do PISF, a partir da aplicação do modelo AcquaNet. As principais demandas de água outorgadas identificadas foram, no reservatório Poções, o abastecimento público (1), e no reservatório Epitácio Pessoa, o abastecimento público (1) e a irrigação (583). Os cenários de alocação de água mostraram déficits no atendimento ao abastecimento público e a irrigação, nas simulações com e sem as águas do PISF, porém, nos cenários com águas do PISF, ou quando este entregou maior vazão, estes déficits foram reduzidos. Os resultados desta pesquisa trazem informações que subsidiam a tomada de decisão para gestão sustentável da água e garantia dos usos múltiplos da água, contribuindo com a melhoria da qualidade de vida da população beneficiária.

Palavras-chave: Uso sustentável da água. Semiárido. Oferta hídrica. AcquaNet.

ABSTRACT: To mitigate the problems derived from the water shortage in the semi-arid northeastern region, the São Francisco River Integration Project (PISF) is being developed, transferring waters from the São Francisco River to other watersheds in the states of Pernambuco, Ceará, Rio Grande do Norte, and Paraíba. The sustainable management of these flows will be vital to guarantee their uses. This research aimed to evaluate scenarios of water allocation for public supply and irrigated agriculture, in order to assist in the management of water resources and the maintenance of these uses in the upper course of the Paraíba River (PB), East Axis of the PISF. The evaluation of multiple uses was carried out through the analysis of the permits issued for the Poções and Epitácio Pessoa reservoirs in 2019. Water allocation scenarios were undertaken considering the presence and absence of the PISF waters, based on the application of the AcquaNet model. The most significant water demands identified were, in Poções reservoir, public supply (1), and in Epitácio Pessoa reservoir, public supply (1) and irrigation (583). The water allocation scenarios showed deficits in meeting public supply and for irrigation in the simulations with and without PISF waters; however, in the scenarios involving PISF or when it provided a greater flow, these deficits

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were reduced. The results of this research provide information that contributes to decision-making for sustainable water management and to ensure the multiple uses of water, contributing to the improvement of the quality of life of the beneficiary population.

Keywords: Sustainable use of water. Semiarid. Water supply. AcquaNet.

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INTRODUCTION

In Brazil, the main usages of water are for urban and rural water supply, animal feeding, irrigation, industrial, mining, energy generation, navigation, fishing, aquaculture, tourism, and leisure (Ana, 2020). Irrigated agriculture is one of the largest consumptive uses of water, often occurring in basins with water deficit in the country. In the semi-arid region, irrigation is essential for agricultural expansion and regional development, with representative job and income generation; however, management has been a challenge (Ana, 2019b).

The evolving consumptive uses of water are tied to economic and population development (Ana, 2019a) and, consequently, have generated pressure on water resources (Sobral *et al*., 2018), acting as a limiting agent for economic activities, especially in the semi-arid region, a region with irregular hydric availability and a deficit in access to water.

The relevant problems regarding the use of water resources in the semi-arid region are related to the balance between demands for access to water use, in quantitative and qualitative terms, with the water supply (Ana, 2019b; Shimizu *et al.,* 2020).

A report published by Ana (2017b), calls attention to the fact that, from mid-2012 to 2016, the drought hit the semi-arid region and caused a sharp reduction in the volume of water stored in the Northeast Equivalent Reservoir, which is the sum of the volume of reservoirs with a capacity above 10,000,000 m^3, mainly in the states of the Northern Northeast (Ceará, Rio Grande do Norte, Paraíba and Pernambuco), with strong expression in the semi-arid area. As a reflection of this 5-year drought, in December 2016, a total of 65 dams that provide water for public supply were dry, and the remaining water volume corresponded to 11.5% of the total storage capacity.

Thus, water scarcity has led to the adoption of rules restricting the use of water resources. These range from limits on water withdrawal from springs to strict rationing.

In this context, some alternatives to provide water in semi-arid regions in the Northeast have been strategically applied, among them the Integration Project of the São Francisco River with Basins of the Northeastern Brazil (PISF), which aims to ensure water security for about

12 million people in 390 municipalities in the states of Pernambuco (PE), Ceará (CE), Rio Grande do Norte (RN) and Paraíba (PB), previously executed by the Ministry of National Integration (MI) and currently by the Ministry of Regional Development (MDR) (Brasil, 2022a).

Ensuring the multiple usages of water is linked to the efficient monitoring of these uses, which is a challenge, especially in the semi-arid region, because the database is scarce, the sampling points are insufficient and the measurements of quantitative parameters present seasonal flaws and low quality. Despite the gaps, the water use control registry carried out by the environmental agencies is an important tool to monitor and evaluate its uses, even if they often fail to reflect the real situation, because the values granted tend to be lower than the real captured. There is still the issue of clandestine withdrawals, difficult to be accounted for (Ana, 2019b).

To assist in the resolution of complex water management problems, the use of mathematical and computational tools capable of developing scenarios assists in planning and decision-making regarding the carrying capacity of hydric resources, allowing to indicate the factors that interfere with the quantity of water, anticipate the impacts resulting from possible hypothetical scenarios, and propose alternatives to find the best solution in watershed management decisions (Mohor; Mendiondo, 2017), as well as in irrigation handling (Borba *et al*., 2022).

Thus, in this study, the modeling of water allocation acts as a tool to support decision making regarding the conditions for meeting the multiple uses of water in the Upper Course of the Paraíba River, in the State of Paraíba. The results obtained contribute to the development of public policies for the management and sustainable use of aquatic resources and the generation of information on the monitoring and evaluation of the multiple uses of water in the Eastern Axis of the São Francisco River Integration Project.

2 MATERIAL AND METHODS

2.1 STUDY AREA

The hydrographic basin of the Paraíba River, which is situated in one of the driest regions of Paraíba State in Brazil, presents low rainfall rates and poor rainfall distribution, with annual averages ranging from 5.0 mm to 64.2 mm (2011 to 2019) and a maximum of 297.90

mm in 2019 (Aesa, 2021). The most pronounced rainfall in the semi-arid region occurs in an average of three months during the year, but the period between 2012 and 2016 was characterized as dry years (Ana, 2017b), with low average monthly precipitation, ranging from 0.0 mm to 43.7 mm (Aesa, 2021).

The referred basin has an area of 20,071.83 km^2, corresponding to 34% of the state territory and drains totally or partially the lands of 85 municipalities, representing 53% of the population of the state (Paraíba, 2006a). It is divided into the sub-basin physiographic regions of the Taperoá River and the Upper, Middle and Lower courses of the Paraíba River (Paraíba, 2001).

The Paraíba River basin was chosen as a study area within the East Axis of the current arrangement of the Integration Project, being a stretch that has been completed and in operation since 2017. In this research, the Upper Paraíba River region will be considered.

The water flow of the São Francisco River on the Eastern Axis of the PISF begins with the capture of the waters in the Itaparica reservoir, in the State of Pernambuco (PE), where part will be conducted to the Poço da Cruz dam - PE, located in the upper course of the Moxotó River, also a tributary of the São Francisco River. And part is conducted to the Paraíba river basin, through channels and stored in reservoirs, Poções and Camalaú, being launched into the Monteiro river, a tributary of the left bank and the main source of the Paraíba river, until it reaches the Epitácio Pessoa reservoir (in the municipality of Boqueirão), in the upper course of the Paraíba river and then in the Argemiro Figueiredo reservoir (in the municipality of Acauã), in the middle course of the Paraíba river (Brasil, 2022b).

The Upper Course region of the Paraíba River drains an area of approximately 6,717.39 km^2 and covers the municipalities of Monteiro, Camalaú, Congo, São João do Cariri, Cabaceiras, Barra de São Miguel and Boqueirão. In this region the main public reservoirs are the Epitácio Pessoa, Sumé, Cordeiro, Poções and Camalaú (Paraíba, 2001). These reservoirs are configured as important sources of water resources for the region and their waters are the object of several conflicts for multiple uses.

The Upper Course region was selected because it contains one of the main reservoirs of the state, the Epitácio Pessoa reservoir. Besides this one, the Poções and Camalaú reservoirs were also considered in the research (Table 1).

Table 1. General characteristics of the studied reservoirs

		Reservoirs		
Características	**Unit**	**Poções**	**Camalaú**	**Epitácio Pessoa**
Operator	-	National Department of Works Against Droughts (DNOCS)	Water and Sewage Company of Paraíba State (CAGEPA)	National Department of Works Against Droughts (DNOCS)
Municipality (PB)	-	Monteiro	Camalaú	Cabaceiras, Barra de São Miguel e Boqueirão
Total annual inflow volume	m^3	28,98	48,17	337,25
Drainage area	km^2	670,0	1.061,4	12.394,5
Volume (capacity)	m^3	29.861.562	48.107.240	466.525.964
Extension of the main dam	m	206,00	320,00	347,00
Main uses	-	Public supply, aquaculture, industrial.	Public supply, aquaculture	Public supply, irrigated agriculture, aquaculture, artisanal fisheries.
Estimated population served	Inhabitants	30.852	10.145	642.260

Source: Ana (2017a); IBGE (2010); Aesa (2022).

2.2 METHODOLOGICAL PROCEDURES

2.2.1 Input data

Reservoir data

AcquaNet works in an integrated way with Geographic Information Systems (GIS) through the loading of shapefiles. The topology and attributes of the basin were obtained from satellite images and the database of the ottobasins from SNIRH/ANA, manipulated in QGis, to delimit and characterize the Upper Paraíba River region, with the quota-area-volume curves of the reservoirs and evaporation rates.

Water resources demands

The evaluation of the volumes and flows required for the Upper Paraíba River region was developed using data from water resource use permits granted by the National Water and Basic Sanitation Agency (ANA), available at https://www.ana.gov.br/regulacao/principais-servicos/outorgas-emitidas.

Regarding the selection criteria for the grants, it was decided to select all those with an ongoing validity period in the study reservoirs. The grants analyzed were available until December/2019. Consistency analysis was performed for the raw data issued by ANA. There were no concessions released for the Camalaú reservoir during the study period.

Natural Flows

The intermediate natural flows adopted in the allocation analysis in the Upper Paraíba River were obtained through the correlation of the observed rates of three river gauging stations and the ratio of intermediate drainage areas in the points of interest. The AcquaNet model was used to perform the hydrological balance in the flow network, seeking to represent the observed operation in the Epitácio Pessoa reservoir. Linear regression was used to calculate the specific inflows into dams, and for the fluviometric stations.

The flow data were obtained from the following fluviometric stations: Caraúbas, Poço de Pedras and Bodocongó, operated by ANA and made available through the Hidroweb platform (http://hidroweb.ana.gov.br/). A historical series of 50 years of data was adopted, from January 1970 to December 2019.

The flows observed at the Caraúbas station served as a basis for adjusting the monthly inflows into the Poções and Camalaú reservoirs. The affluent monthly water levels in these reservoirs were calculated by multiplying the ratio of the monthly water level and the specific runoff of the Caraúbas data input by the specific runoff of each station. The monthly inflows to the Epitácio Pessoa reservoir and Bodocongó station were calculated by multiplying the sum of the monthly inflows and the sum of the specific outflows of the Caraúbas and Poço de Pedras stations by the specific rate estimated at the above mentioned points.

The intermediate monthly flows at Camalaú, Caraúbas and Epitácio Pessoa are calculated by subtracting the ones generated in the respective upstream drainage areas. In order to avoid negative values, the monthly flow at the Bodocongó station is the minimum between the calculated flows at Epitácio Pessoa and Bodocongó and the value observed at the fluviometric station.

2.2.2 AcquaNet Model

AcquaNet performs sequential optimization without prediction and can be treated as a simulation model by means of which hundreds or thousands of years of historical or synthetic flow data can be used. It performs a statistical analysis that allows determining, on a scale from 0 to 100% of the time, what the flow rate will be in all links of the flow network (river stretches), considering the series of flows used by the model. In this research the water allocation module was used, and the model of its operation in AcquaNet will be presented according to Porto *et al*. (2003).

The program performs the calculations in two ways and in this work the Continuous Simulation method was used, in which the most important value is the total number of simulation years (NT). In this method, series of monthly affluent flows with duration equal to NT were provided. The model performed the calculations continuously, for all the existing years. At the end of the calculation, the results were provided monthly for all years. The resulting series lasted for 50 years.

The representation of the water body in AcquaNet consists of a trace composed of nodes and arcs. These may represent reservoirs, basin demands, confluence points between rivers, water import points from one basin to another, or just water passage nodes in the basin. Furthermore, the arcs are the connecting links between the nodes and represent stretches of rivers, natural or artificial channels. The AcquaNet network of the Upper Paraíba River was composed by 3 reservoirs, 7 demands (2 for public supply and 5 for irrigation), 9 passage nodes and 29 links.

To formulate the network layout in AcquaNet, the demand nodes were inserted taking into account the consumptive demands of public supply and irrigation, as well as the environmental flows downstream of the reservoirs. The model meets the demands according to a priority value (P) assigned by the user, which can vary from 1 to 99 (the value 1 is the highest priority). Priorities P are related to costs C in a biunivocal way ($C = 10P - 1000$), which means that the values of C representing priorities are always negative. Therefore, by meeting a priority, the allocation module decreases the network costs by a value C per unit of delivered flow.

For ecological demands, Priority 1 was assigned. For public supply demands, Priority 5 was assigned, and for irrigation, Priority 15. The environmental demands were defined according to the sustainable use of water focused on the main use, namely public supply. The ecological demands are necessary for the minimum maintenance of aquatic organisms.

The operation of the reservoirs was done using the concept of target volume or level in which a priority is assigned. In this way, whenever the stored volume is smaller than the target volume, it will hold water as long as the other priorities of the network are smaller. The volume stored above the target level has zero cost, that is, it is free to meet any demand, no matter how low its priorities are. Reservoir evaporation losses are taken into account through an iterative process (Porto *et al*., 2003).

The Target-Volume of Epitácio Pessoa reservoir was assigned a Priority 10, aiming at meeting the public supply demand in periods of scarcity. The Target-Volumes of Poções and Camalaú were given Priority 30, so that the transfer of water to the Epitácio Pessoa was assured. The demands related to the Spillover Volume, 85, as the last priority so that the reservoirs primarily meet the demands before releasing water downstream. The Drain (model adjustment element), was assigned Priority 99. When all demands cannot be met, the first to suffer deficits will be those with the lowest priority value.

Thus, the flow network of the model was established to represent the operation criteria of Poções and Epitácio Pessoa reservoirs, considering the current process of Water Resources Use Granting and the PISF. Such criteria were obtained through the evaluation of the data issued by ANA, through REGLA and regulatory frameworks. No grants were issued for the Camalaú reservoir during the study period. Therefore, the aforementioned dam composes the network only at the level of characterization and operationality of the basin.

The water allocation of the AcquaNet system is done as follows: the model solves the optimization problem of the flow network defined by Equations 1 to 4, composed of a set of arcs and nodes that represents the water system. The decision variable is the flow that goes through the arcs to meet the demands. The water balance is given by Equation 4. The time interval adopted in the analysis was monthly. In the reservoirs the model adopts a complete mixing pattern (Porto *et al*., 2003).

$$\sum_{i=1}^{n}\sum_{j=1}^{n} C_{ij} \cdot Q_{ij} \tag{1}$$

$$\sum_{i=I_j}^{n} Q_{ij} - \sum_{i=O_j}^{n} Q_{jk} = 0 \tag{2}$$

$$_{ij} \leq Q_{ij} \leq U_{ij} \quad \forall\ i.j = 1,\ldots,n \tag{3}$$

$$V_t = V_{t-1} + I_t - E_t - w_t - Q_t \tag{4}$$

In which:

Q_{ij} - Flow rate passing through the arc (i, j) defined by start node i and terminal junction j during the required time interval t;
Q_{jk} - Flow rate passing through the arc (j, k) defined by start node j and end node k, during the required time interval t;
C_{ij} - unit cost associated with the flow rate Qij, (weighting factor that represents operational water rights or priorities, being a negative cost is treated as a benefit);
I_j - set of all nodes with arcs that are terminated at node j (i ϵ Ij means all nodes i that are elements of the set Ij);
O_j - set of all nodes with arcs arising from node j;
I_{ij} - minimum flow rate in the arc (i, j);
U_{ij} - maximum flow rate in the arc (i, j);
V – reservoir volume in period t;
I – natural inflow to the reservoir in period t;
Q – flow out of the reservoir in period t;
E – reservoir evaporation in period t;
w - is the volume spilled into the reservoir in period t.

The input data are the natural inflows to the reservoirs, the capacity and quota-volume curves found in the tanks, the capacity of the arches, as well as the demands and priorities of the reservoirs' needs and target volumes. The calculation option adopted in the solution of the flow network optimization was Hydrological States, where the model considered the amount of water stored in the reservoirs to determine which value of demand, of target volume and the strategies used in the calculation of each of the months (Porto *et al*., 2003).

2.2.3 Scenarios

In order to produce the water allocation scenarios, only the Poções and Epitácio Pessoa reservoirs were considered because they are the only ones in the study area to have legalized consultative demands.

The water allocation scenarios considered different input flows, where: scenario 1 - simulation was performed without PISF water input, considering only the natural flows of the sub-basin in the period from 1970 to 2019; in scenario 2 - monthly averages of PISF flows for the years 2017 to 2019, made available by the MDR, were added and extrapolated for the 50 years used in the modeling (1970 to 2019); in scenario 3 - simulation was performed considering only the months of water inflow from the PISF, with original flows provided by the MDR, in the years 2017 to 2019; and in scenario 4 - the simulation considered the maximum continuous flow rate predicted in the project for the East Axis, of 10 $m^3 s^{-1}$ (2017 to 2019) (Castro, 2011).

The setting of the scenarios occurred so as to allow the analysis of the influence of the PISF waters on the water allocation of the Upper Paraíba River in a 50-year period, and simulations specifically in the first three years of PISF operation (2017 to 2019), considering the climatic trends and the general characteristics that have been occurring in the sub-basin.

Thus, in scenarios 1 and 2, it was possible to make a projection of what is the profile of water allocation in the study area in the next 50 years, without and with the PISF, respectively, what is the level of fulfillment of demands in the Poções and Epitácio Pessoa reservoirs, and what type of optimized water allocation operation is indicated by the model.

In scenario 3, the objective was to observe a more reliable influence of water allocation in the study area with the arrival of the PISF waters. In scenario 4, the purpose was to observe what would be the influence on water allocation if the project were working under optimal conditions (forecasted flow) in the first three years of operation.

3 RESULTS AND DISCUSSION

3.1 CALIBRATION OF THE SYSTEM FLOW RATES

Due to the lack of continuity of the historical flow series in the existing river gauging stations in the basin, it was necessary to fill in the gaps in the analysis period for some stations. AcquaNet was configured to represent the volumes of the Epitácio Pessoa reservoir and estimate the inflows to balance the water balance.

A very small difference can be observed between the values of the volumes monitored in the Epitácio Pessoa reservoir and those calculated with the water balance in the flow network with AcquaNet. The relative bias (ratio between the average error of the observed and simulated values, and the average applied volume) was - 1.7%, showing an insignificant gap between the values.

The estimated effluent water levels obtained at the Bodocongó station showed a satisfactory fit between the effluent volumes at this station (R^2 = 0.736), with an average underestimate of the calculated flows of approximately 27%. Based on these results, the method used to estimate the system's intermediate natural drainage was considered valid. Maximum priorities for meeting demands and the observed target volumes were assumed. The flows discharged into the reservoirs were calculated in AcquaNet and the inflows to them were estimated by means of a water balance.

3.2 SCENARIOS FOR MEETING THE DEMANDS GRANTED

Among the consumptive and authorized uses in the study area, public supply and irrigation were identified. The demand entitled PISF, in the following scenarios, also refers to the provision of public water resources, and is highlighted because it is a new demand in the basin.

In the Poções reservoir, the main use is for public supply. However, other uses have been reported in the literature previously, such as irrigation and aquaculture (Ferreira, 2016; ANA, 2017a). In 2019, only one grant was identified for the right to use water in the Poções reservoir, issued by ANA, through the National Registry of Users of Water Resources (CNARH). It was issued from 2004 to 2024, for the purpose of public supply.

The allocation issued for the Poções reservoir, in order to supply the public (CAGEPA), demanded a volume of 1,055,492 m^3 $year^{-1}$, corresponding to a flow of 0.40 m^3 s^{-1}. This value corresponds to a monthly flow of 0.033 m^3 s^{-1}.

In the Epitácio Pessoa reservoir, 583 grants were identified for irrigation and one grant for public supply (CAGEPA), issued by ANA for the right to use water in 2019. Despite the greater number of licenses given for irrigation, the flows authorized for public supply corresponded to 67%. The requesting users of the Epitácio Pessoa reservoir are distributed in three municipalities, Barra de São Miguel corresponding to 11%, Boqueirão representing 81% and Cabaceiras, with 8%.

The public supply in the Epitácio Pessoa reservoir represents a volume of 8,227,957 m^3/year, followed by irrigation, with a volume of 5,127,844 m^3 $year^{-1}$, corresponding to 3.2 m^3 s^{-1} (67%) and 2 m^3 s^{-1} (33%), respectively.

Among the crops authorized for irrigation, onions (25%), peppers (22%) and beans (21%) stand out. Regarding the crops granted with the highest individual water demand, cauliflower is the one that has been granted 0.0064 m3 s^{-1} for its cultivation and only one user, but the highest water demand is for the temporary crops of beans (21%), peppers (21%) and onions (26%), since they are the most cultivated when comparing the numbers of requests for allowances.

3.2.1 Scenario analysis: 1 - with PISF and 2 - without PISF

Comparing scenarios 1 and 2, it was possible to observe that, after the entry of PISF waters (scenario 2) in the Poções reservoir, there was an increase in the percentage of public supply. The service deficit decreased from 42% in scenario 1, without project waters, to 4% in scenario 2, with PISF waters (Figures 1A and 1B).

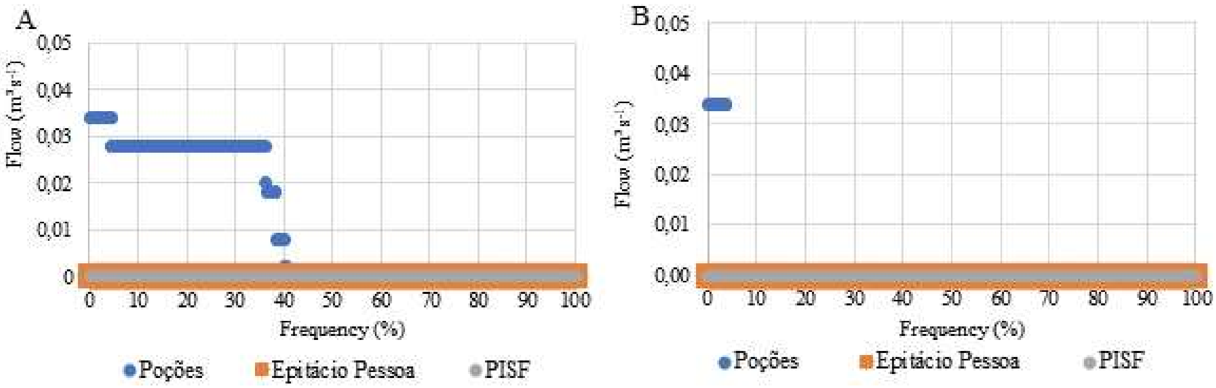

Figure 1. Steady curve of the service deficit for public supply in the Poções and Epitácio Pessoa reservoirs and PISF (SIAA - Campina Grande and Cariri), simulated in the period from 1970 to 2019: A: Scenario 1 - without influence of PISF waters and B: Scenario 2 - with presence of PISF waters
Source: The authors (2021).

Scenario 2 presented 1 year and 11 months of service failure and the deficit flow was equivalent to the total demand required (0.034 $m^3 s^{-1}$) in this period. In scenario 1, the deficit period varied during 41 years, observing years with deficit of only 1 month and years with deficit during all 12 months. Adding up the months with sequential deficits, a total of 20 years and 8 months of service failure is observed.

The demands for drinking water supply, applied in scenarios 1 and 2, were 0.034 $m^3 s^{-1}$ in the Poções reservoir, 0.266 $m^3 s^{-1}$ in the Epitácio Pessoa reservoir and 1.17 $m^3 s^{-1}$ for the PISF. The public supply provided by the Epitácio Pessoa reservoir did not present a deficit and if there had been an interruption of flows from PISF during the study period, it could also have been fully supplied. The same scenario was observed for meeting the public supply demand coming from the PISF.

A deficit was identified regarding irrigation demand, exhibiting a reduction in scenario 2 (Figure 2A and 2B). Emphasizing the importance of the results obtained for local socioeconomic development and maintenance of agricultural activities.

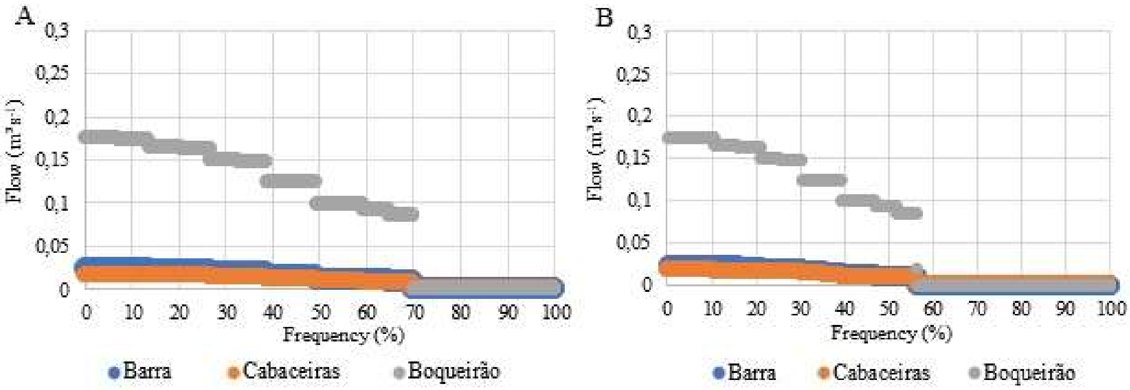

Figure 2. Steady curve of the service deficit for irrigation in the municipalities covered by the Epitácio Pessoa reservoir, simulated in the period from 1970 to 2019: A: Scenario 1 - without influence of PISF waters and B: Scenario 2 - with presence of PISF waters
Source: The authors (2021).

It was observed in scenario 1, the occurrence of deficits in irrigation supply in 70% of the time, in the three municipalities that correspond to the area of influence of the Epitácio Pessoa reservoir, corresponding to a period of 35 years. On the other hand, in scenario 2, the deficit fell to approximately 56% of the time, corresponding to a period of 28 years and 2 months (Figure 2 B).

In the critical periods of drought between 1998 and 2002 and from 2012 to 2016, the allocation of water in the basin resulted in water supply compromise in the cities served by the Epitácio Pessoa reservoir. In these periods the supply of water was not completely ceased, but rationed, reaching a water supply cut of 84 hours per week in November 2015, being saved from a supply collapse with the arrival of the PISF waters (Rêgo *et al*., 2017).

In scenario 1, the model managed to optimize the allocation of water for priority use in the dry periods between 2012 and 2016, without compromising the demand for public supply. For this, irrigation demands were affected and the volume of water in the reservoir was saved (Figure 3).

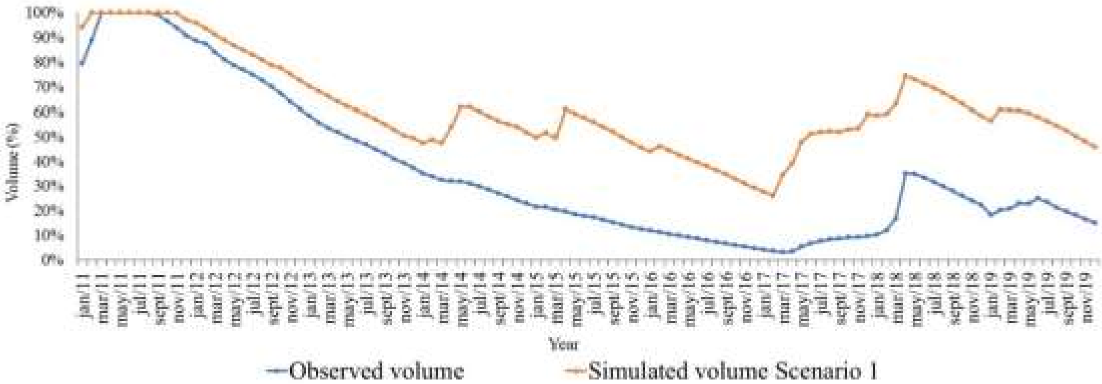

Figure 3. Percentage of volumes (%) reached in the Epitácio Pessoa reservoir in relation to total capacity, in the years 2011 to 2016.
Source: The authors (2022).

According to Rêgo *et al*., (2017), hence, rationing in the municipalities supplied by the Epitácio Pessoa reservoir could have been avoided or minimized, delaying its onset to almost 2 years ahead and occurring more mildly, if a set of more efficient and sustainable measures in water management had been adopted, especially those related to the fulfillment of grants.

Lucena (2018), found from the simulation of scenarios with different water management solutions, that with surveillance and limitation of secondary withdrawals of water from the reservoir, including in the years of highest inflow, the encouragement of control measures to combat losses and the rational use of water, the Epitácio Pessoa reservoir would not have reached alarming levels in water volume and the collapse in public supply to more than half a million inhabitants would have been mitigated.

It was considered in the simulations the fulfillment of the environmental demand estimated for the basin area under study and it was found that a minimum flow rate of 0.3 $m^3 s^{-1}$ was always met in the scenarios worked. This requirement was evaluated in order to verify the minimum ecological flow fully met, without compromising the other demands (Santos; Cunha, 2013).

3.2.2 Scenario analysis: 3 - actual flow and 4 - maximum flow

In scenarios 3 and 4, for public supply demand, there was a deficit in the Poções reservoir only in scenario 3, and that with the increase of the flow rate to 10 $m^3 s^{-1}$ (scenario 4), there has been an advance in the availability of water for allocation. The deficit was reduced from 61% in scenario 3 to 8% of the time in scenario 4 (Figure 4), representing full coverage in 22 months in scenario 4 and in three months in scenario 3.

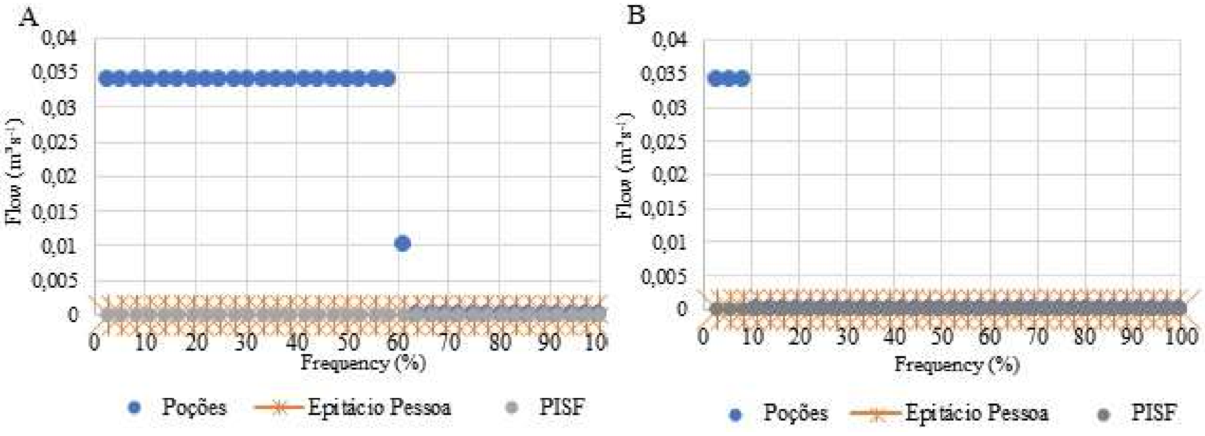

Figure 4. Steady curve of the service deficit for public supply in Poções and Epitácio Pessoa reservoirs and PISF (SIAA - Campina Grande and Cariri), simulated in the period from 2017 to 2019: A: Scenario 3 - with flow operated in the Project and B: Scenario 4 - with flow of 10 m³ s^{-1}
Source: The authors (2021).

The deficits in meeting public supply demand observed in scenario 3 occurred in November/2017 and were distributed over the remaining years, while in scenario 4, they occurred between July and September 2018.

For irrigation, there was some deficit in supply at 84% of the period (32 months) in scenario 3, while in scenario 4, shortfall in supply occurred at 22% (8 months) of the studied timeframe (Figure 5A and 5B). In scenario 3, in the period between December 2017 and April 2018, the demand was fulfilled in the municipalities studied, with the exception of January 2018, without reaching the demand in Cabaceiras, and partial coverage in Boqueirão. In scenario 4, the months from January to August/2017, were the only months with a deficit in attendance.

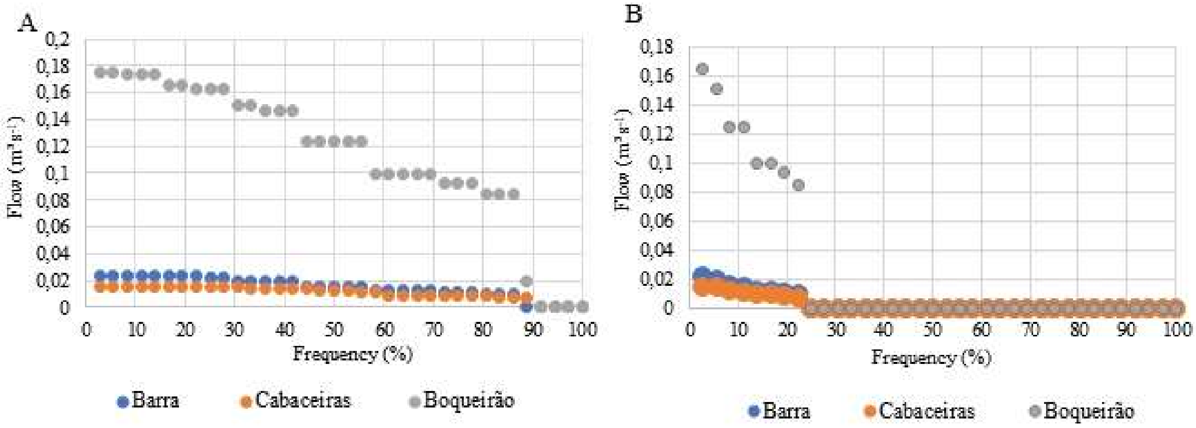

Figure 5. Steady curve of irrigation attendance deficit in the cities covered by the Epitácio Pessoa reservoir, simulated in the 2017-2019 period: A: Scenario 3 - with flow operated in the Project and B: Scenario 4 - with flow of 10 m³ s^{-1}
Source: The authors (2021).

The deficits observed in meeting irrigation demands in the Epitácio Pessoa reservoir, in scenarios 3 and 4, occurred because the model prioritized the sustainability of serving public supply and maintaining a volume quota in the water reservoir.

In figure 6, it is observed that the original volumes seen in the reservoir reached a maximum of 30% of total capacity in April 2018, indicating that the managers' priority was to meet all demands, even if the volume of the latter reached low percentages.

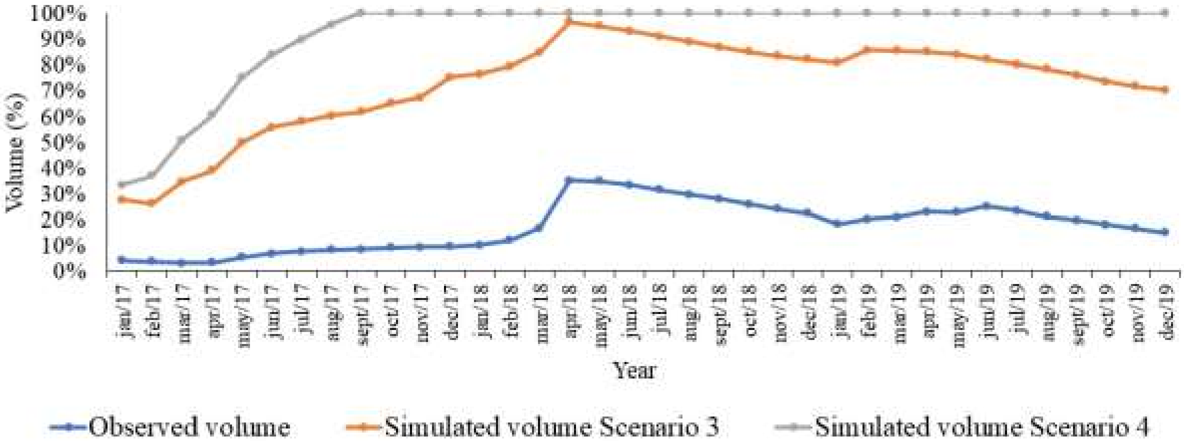

Figure 6. Percentage of the volumes (%) reached in the Epitácio Pessoa reservoir in relation to the total capacity, in the years 2017 to 2019
Source: The authors (2022).

The results of the simulations observed in scenarios 3 and 4 demonstrate an increase in the outflow of the PISF, even if in a continuous way, there are still problems with meeting the allocated demands, drawing attention to the priority use in the Poções reservoir. These data show that management agencies need to be cautious in the release of new water use permits in the region and that it is necessary to focus on initiatives that prioritize water saving, change in use patterns and waste reduction (Niayifar; Perona, 2017; Rêgo *et al*., 2017; Roobavannan *et al*., 2017; Shourian; Mousavi, 2017).

Araújo and Oliveira (2021) highlighted that in order to meet the demands of the Epitácio Pessoa reservoir it is necessary to implement mechanisms to increase water efficiency in the region, as an example, one can mention the assistance to irrigators regarding the deployment of more efficient irrigation techniques. Rêgo *et al*. (2017) disapprove the water management developed in the Epitácio Pessoa reservoir during dry years, emphasizing the lack of suitable instruments and sustainable measures implementation and inadequate management focused on meeting the legal rules of granting.

Agricultural crops predominate among the grants in the Epitácio Pessoa reservoir, and these have been cultivated initially by family production by riverside people, later structured with a focus on larger scale commercialization (Silva, 2012). Among the 28 crops present in the region, with authorized grants, onions (25%), peppers (22%) and beans (21%) stand out. The most used irrigation system is drip (98%). This irrigation technique is considered the most efficient among those used in Brazil, with a reference efficiency of 95% (Ana, 2004).

For irrigated agriculture activities, conditions were established for the use of water in the reservoir in the pre-operation of the PISF. Such conditions included a limit of abstraction up to a maximum of 8.5 h/day, but it was possible to observe that the abstraction was realized for 13 h/day. In addition to being determined to allow only temporary crops, seedlings and pastures, the release of grants for permanent crops, such as: orange, banana, passion fruit, papaya and pepper, and the issuance of three grants with the use of a not allowed irrigation system, the sprinkling technique (banana cultivation) (Ana; Aesa, 2018).

Conflicts over the use of water in the Paraíba river basin are challenges for the management of water resources and with the arrival of water from the São Francisco river, the demands and development of economic activities that use water also increase, which is why it is essential to carry out constant reassessment of the issued grants and technical analysis for the issuance of new grants (Morais *et al.,* 2020), considering, above all, the types of agricultural crops appropriate for the local water situation and which are the favorable time of the year to cultivate them.

4 FINAL CONSIDERATIONS

The main uses of water identified in the Upper Paraíba River are public supply (priority) and irrigation. The scenarios for meeting demands revealed a shortage of public supply from the water captured in the Poções reservoir and irrigation demands in the Epitácio Pessoa reservoir in scenarios 1 - without PISF waters and 2 - with PISF waters. However, in scenario 2 this deficit was reduced by 38% according to the simulation of meeting public supply and 14% according to the simulation of meeting irrigation demand. Thus, there was an increase in the percentage of these demands met in scenario 2.

During the drought periods from 2012 to 2016, the model was able to solve the water allocation problem without compromising the demand for public supply in the Epitácio Pessoa reservoir, but to do so, the irrigation demands were affected and the reservoir water volume was saved.

When comparing scenario 3 - considering real flows from the PISF with scenario 4 - considering flows of 10 m^3 s^{-1}, in the first three years of the Project's operation (2017 to 2019), an increase in the percentage of water supply and irrigation demands in scenario 4 was observed, but there were also deficits in the delivery of water to meet demands in both scenarios. The deficit in public supply reduced from 61% in scenario 3 to 8% in scenario 4, and for irrigation, a reduction from 84% in scenario 3 to 22% in scenario 4 was observed.

In addition, the model prioritized the maintenance of the public supply and the safe water volume in the Epitácio Pessoa reservoir. Analyzing the water volumes in the Epitácio Pessoa reservoir, it is possible to identify that the managers' priority was to meet all demands, even if its volume would reach low percentages, different from the measures adopted in the simulation.

Caution and planning are necessary when issuing new grants and maintaining those that are not a priority, to ensure the conservation of the multiple uses of water in a sustainable way and the ecological conditions of the aquatic ecosystem. The results of the scenarios show that water supply sustainability in the upper reaches of the Paraiba River, especially for public distribution, is dependent on optimized water allocation.

Water resource management must focus on preventive planning for climate change, effective operational management of the flow of water from the Eastern Axis of the PISF, efficient planning of water allocation, with more influential participation by civil society, and the application of technologies that make it increasingly possible to understand information about water resources and to examine the impacts and the resilience of the ecosystem in question, so that effective improvements can be seen in the lives of the populations that will benefit from the arrival of the PISF waters.

It is expected that the results of this research will serve as tools of analysis, experience and learning for water management in the Upper Paraíba River and the East Axis of the PISF. It is hoped that it can promote reflections and subsidize the decision making processes, in order to guarantee the public supply and other uses of water in the basin, in a sustainable way, promoting improvement in the quality of life of the beneficiary population.

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