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Reservoir operation in the context of inter-basin water transfer

Operação de reservatórios no contexto de transferência de água entre bacias hidrográficas

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ABSTRACT

Inter-basin water-transfer projects are used as a possible solution to increasing water scarcity in many regions, but these projects are often expensive and require large infrastructures, so their benefits need to be maximised and their costs reduced. In this context, this study's objective was to define technical criteria to operate water reservoirs in the context of water transfer between river basins by using Brazil's Armando Ribeiro Gonçalves (ARG) reservoir in the state of Rio Grande do Norte, one of the reservoirs receiving water from the São Francisco River Integration Project (PISF), as a case study. The results demonstrate that using hydrological conditions to define when and how much water to transfer is extremely important for water resource management, as it increases reservoir efficiency and reduces transferred volumes, thereby cutting costs.

Keywords: Exogenous flow; Optimisation; São Francisco River Integration Project.

RESUMO

Os projetos de transferências de água entre bacias hidrográficas se apresentam como uma possível solução para o aumento de escassez hídrica em diversas regiões. Porém, estes projetos são frequentemente caros e necessitam de grandes infraestruturas, sendo necessário, portanto, maximizar os seus benefícios e reduzir seus custos. Nesse contexto, o objetivo deste estudo é a definição de critérios técnicos para operação de reservatórios no contexto de transferência de água entre bacias hidrográficas, tendo como área de estudo o reservatório Engenheiro Armando Ribeiro Gonçalves (ARG) no estado do Rio Grande do Norte, um dos açudes receptores das águas do Projeto de Integração do Rio são Francisco (PISF). Os resultados demonstram que o uso de condições hidrológicas para definição de quando e quanto transferir, é de extrema importância para o gerenciamento dos recursos hídricos, pois aumenta a eficiência do reservatório, reduz os volumes transferidos e, consequentemente, os custos dessa atividade.

Palavras-chave: Vazão exógena; Otimização; Projeto de Integração do Rio São Francisco.

INTRODUCTION

Rainfall occurrence and varying demands for water use have spatial and temporal heterogeneity, i.e., they are distributed unevenly in various regions and countries worldwide. Furthermore, water demands have increased substantially in recent decades due to the economic development and population growth (Zhou et al., 2017; Zhu et al., 2014), increasing the risk of water scarcity.

In semi-arid regions – which naturally present significant inter-annual hydrological variability, experiencing consecutive years with water deficits interspersed with years of high rainfall – the difficulty of meeting the population's demands becomes more evident (Nunes et al., 2016; Studart & Campos, 2001). In these regions, one traditional solution has been to construct reservoirs, which potentially can reduce the difference between water demand and supply, in which water is stored during the rainy season for use during dry periods, thereby providing an important resource for water supply regularisation.

However, in some situations, increasing demand exceeds the reservoirs' regularisation capacity, rendering water-transfer projects between river basins an important engineering measure that aims to guarantee access by transferring water resources from a basin with greater water availability to another with greater supply needs, i.e., these projects provide improved water access through artificial reallocation to mitigate the uneven distribution of water resources (Sadegh et al., 2010; Wang et al., 2015; Zhou et al., 2017).

However, water transfers between basins, despite being viewed as a technical solution to supply populations' water demands, are often expensive, requiring large infrastructures and energy for pumping (Andrade et al., 2011; Zhu et al., 2014). These logistical and financial realities signal the need for technical studies that can identify more aggressive ways to implement effective reservoir operation regulations related to water-transfer projects (Sadegh et al., 2010) that maximise benefits and reduce costs.

The main objective in reservoir operations is to determine the best allocations to maximise overall benefits while satisfying varying needs, thereby allowing for a reconciliation between supply and demand for water, and preventing or mitigating possible conflicts (Nunes et al., 2016; Vieira et al., 2010). With water-transfer projects, one of the essential elements that also must be considered is the need for a water detour, given that it is the main hydrological connection between donor and receiving reservoirs, and it determines water-transfer costs (Gupta & Van Der Zaag, 2008). Calculating the amount of water to be transferred efficiently will help maximise use of the diverted water and reservoir, reducing losses and making water more available. This characteristic is known as water synergy, which entails better use of reservoir water that was not allocated before the addition of exogenous flows and was lost to spills and evaporation (Aragão, 2008; Farias et al., 2017; Pufal et al., 2019).

Thus, establishing proper reservoir operation rules on when and how much water can be transferred during a specific period based on ideal conditions is one of the biggest technical issues in inter-basin water-transfer projects (Zhu et al., 2014).

The methodologies used to regulate water use from reservoirs and to define their operating rules are diverse and use reservoir operation models, which can be classified as simulation, optimisation, or a combination of the two (Rani & Moreira, 2010). This variation occurs because no standard methodology exists for all reservoir operation studies; thus, the choice depends on several aspects, such as number of reservoirs, purpose of water use, operation time and application stage (Lanna & Lima, 2005). Several kinds of rules are used currently, such as the Standard Operating Policy (SOP), Linear Decision Rule (LDR) and different forms of the Guide Curve Rule (Zeng et al., 2014).

Regarding water transfers between river basins, several studies have examined reservoir operation and addressed several situations. Multiple reservoir operations can be analysed (Gu et al., 2017; Vieira et al., 2010; Abreu et al., 2016), only the donor reservoir alone (Tu et al., 2003). both donor and receiver reservoirs was considerate (Peng et al., 2015; Zeng et al., 2014) to analyse the amount of water diverted from one reservoir to another (Zhu et al., 2014). In optimisation, studies can apply fuzzy logic (Sadegh et al., 2010), two-level analysis optimisation (Guo et al., 2012; Zhu et al., 2017), or a genetic algorithm (Zhu et al., 2014), among other methods (Silva et al., 2017; Pufal et al., 2019; Farias et al., 2017).

Thus, it has been observed that few extant studies have examined how much and when to transfer water from the donor basin to optimisation the operations for receiving reservoir water, what are essential in managers' decision-making and that directly influences water availability and how it will be distributed to the population for various uses.

In this context, this study's general objective is to define technical criteria for the operation of water reservoirs in the context of water transfer between river basins. To achieve the principal objective, two specific subordinate objectives are presented: (i) to evaluate how much future demand the reservoir can satisfy with the desired guarantees, considering a constant transposed flow, and (ii) to analyse when and how much water to transfer to minimise deficits in meeting demands and the transferred volume.

MATERIAL AND METHODS

Study area

The study focussed on the Armando Ribeiro Gonçalves (ARG) reservoir within the Piancó-Piranhas-Açu Watershed (Figure 1), located in the semi-arid region of the Brazilian Northeast between the states of Rio Grande do Norte (RN) and Paraíba (PB). The reservoir has a maximum storage volume of 2,400 hm^3 and a total drainage area of 37,028 km^2, making it the largest water reservoir in RN (Agência Nacional de Águas, 2017).

The ARG reservoir provides water for human and industrial supply, irrigation, livestock and aquaculture needs. According to the Basin Water Resources Plan, total demand from the ARG reservoir is 16.72 m3/s, with only 0.92m^3/s allocated for priority uses (human and animal supply) and a large part of the demand for aquaculture (50.4%) and irrigation (43.4%) (Agência Nacional de Águas, 2016a). As for the minimum remaining flow, no information on this data exists on the reservoir under study.

Although its use for human needs is small compared with other uses, this reservoir plays a significant strategic role in the state's social and economic development, as it supplies water to more than 30 cities, between them cities in other watersheds (Agência Nacional de Águas, 2017).

The ARG reservoir is in a semi-arid climate region (Brasil, 2004) with an average annual evaporation rate of 2,569 mm and precipitation of 554 mm concentrated between February and June, with frequently occurrence of drought (Figure 2). The region's vegetation is predominantly Caatinga, the soils are shallow, and much of the basin lies on a crystalline substrate (Agência Nacional de Águas, 2016a); therefore, most of the rivers are intermittent, i.e., they can remain completely dry for several months or even years at a time (Brasil, 2004).

This reservoir will receive water from the Integration Project of the São Francisco River (PISF). The PISF is one of Brazil's largest inter-basin water-transfer projects, designed to bring water from the São Francisco River to the states of Pernambuco, Paraíba, Ceará and Rio Grande do Norte via two axes (north and east). The transposition-works complex, aside from two main channels with a length of about 477km, includes construction of nine pumping stations, 27 reservoirs, four tunnels, 13 aqueducts, nine 230 kV substations and 270 km of high-voltage transmission lines with a minimum pumping flow in the two axes of 26.4 m^3/s, expected to provide a predicted minimum value of 16.4m^3/s for the northern axis and 10m^3/s for the eastern axis (Agência Nacional de Águas, 2005).

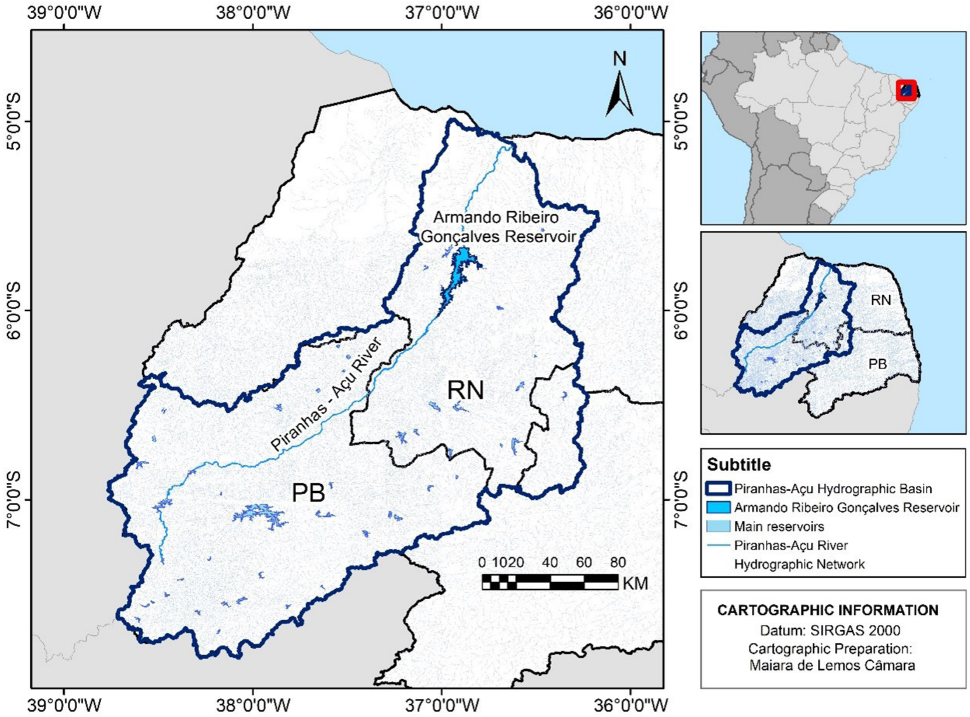

Figure 1. Location of the Armando Ribeiro Gonçalves reservoir.

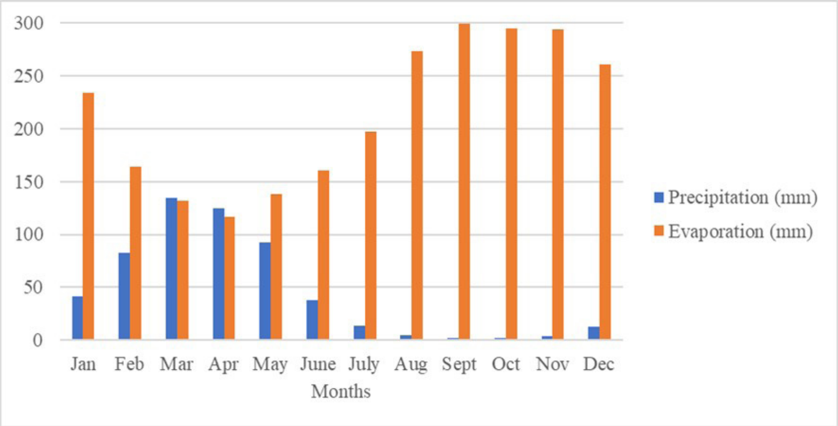

Figure 2. Annual precipitation and evaporation of the Armando Ribeiro Gonçalves reservoir.

PISF's goal is not only to transfer water, but also mainly to support sustainable regional development and reduce socioeconomic differences between the nation's regions. Thus, the prospect is that through PISF's efficacy, the water accumulated in the reservoirs and dams in the receiving basins can be used more efficiently to meet the population's needs and stimulate social and economic development, with consistent improvements in agriculture, livestock, industry and local infrastructure (Brasil, 2004).

Under the agreed-upon rules, RN will receive a constant PISF flow of 2.95 m3/s (Agência Nacional de Águas, 2005), but considering the losses in the water course, estimated in ANA's Technical Opinion No. 19/2016/SRE, 1.97m^3/s will reach the state (Agência Nacional de Águas, 2016b). However, the actual amount of water that will be transferred will be defined in the Annual Management Plan (PGA), the planning instrument for water allocation that each receiving state submits (Molinas, 2019).

Therefore, the PGA is the specific contractual adjustment instrument that the federal PISF operator prepares based on the information that each state submits, containing the schedule for the pumping and supply of raw water at delivery points, including distribution of flows and prices to be charged. To prepare PGAs, states must send their water demands to the PISF Management Council for the following year by August 15 (Brasil, 2017).

Technical operation criteria

To fulfil the study's general objective, simulations of the Armando Ribeiro Gonçalves reservoir and optimisations of the

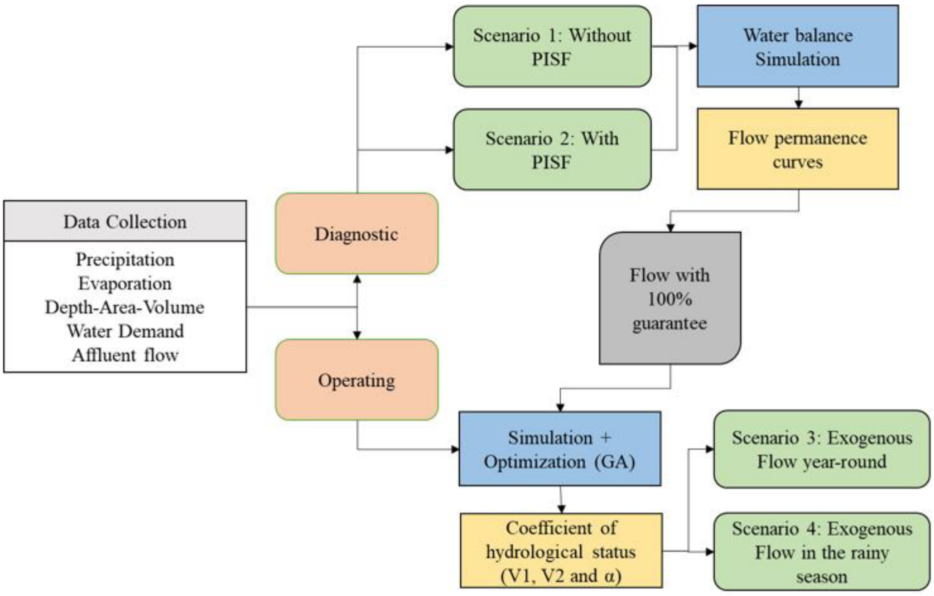

Figure 3. Flowchart of methodological steps.

technical operation criteria were conducted in two approach (diagnosis and operation) while considering variations in exogenous inflow and demands (Figure 3).

In the diagnosis approach, the reservoir was simulated by considering two scenarios: Scenario 1, without exogenous flow from the PISF, i.e., the reservoir's current situation, and Scenario 2, with a constant year-round exogenous flow of 1.97 m3/s from the PISF. In these two scenarios, the regularisation curve were obtained and the regularised flow with a 100% guarantee were used in Scenarios 3 and 4.

Considering that the ARG suffers large variations in its natural hydric availability, the reservoir was simulated, in a second moment, by considering an operational situation with the PISF in full operation. Seeking to minimise the volume to be transferred, the reservoir's hydrological conditions that trigger the need for exogenous water to meet its demands were defined. For this, the water volume stored in the reservoir during August of the previous year was used as an indicator of the reservoir's hydrological condition that would trigger the need to request water from the PISF for the following year. To achieve this goal, two scenarios were considered: In Scenario 3, the transfer would occur constantly from January to December, but in Scenario 4, the transfer would occur in a concentrated way, i.e., only during the first semester (January to June), when the rainy season occur. In both scenarios studied, the volume of water transferred is the same, with Scenario 4 justified by the fact that during the dry period, evaporation rates are higher, influencing the flow of water transferred, mainly water transported to the reservoir.

In this simulation, the reservoir was divided into zones (hydrological states) in which reduction coefficients were applied to the exogenous flow (Figure 4). Thus, when the volume of water stored in the reservoir during August of the current year was in Zone 1 (between V1 and Vmax), it would not be necessary to transfer water to the RN the following year, but if the reservoir during August had a volume between V1 and V2, a partial transfer would be made by applying the reduction coefficient (α), and only when the reservoir had a stored volume during August lower than V2 would the entire PISF flow (Qex) be transferred.

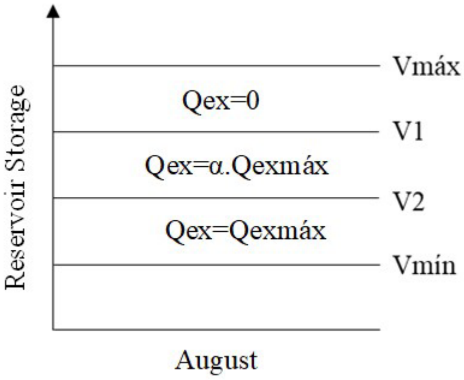

Figure 4. Hydrological status of the reservoir during August for exogenous flow request.

In Figure 4, Qex is the exogenous flow that RN will request in August for the following year; Qexmax is the maximum value of the flow transferred to the reservoir; α is a reduction coefficient applied to the exogenous flow; V1 and V2 are the volumes stored during August that define the limits of the zones to alter the quantity of exogenous flow requested; and Vmax and Vmin are the maximum and minimum reservoir volumes, respectively.

The parameters' optimisation, i.e., the limits of the zones (V1 and V2) and coefficient-of-flow reduction (α), was developed in R language (R Core Team, 2018) using the 'GA' package, developed by Scrucca (2013), based on the simulation of the volume through the water balance.

Reservoir simulation

To perform the simulations proposed in the scenarios, the water balance equation was used, considering or not considering the exogenous water-transfer flow between basins based on Equation 1:

$$S(t+1) = S(t) + Q(t) + \propto . Qex(t) + P(t) - D - E(t) \tag{1}$$

in which S(t+1) is the reservoir volume at the end of month t; S(t) is the reservoir volume at the end of the previous month; Q(t) is the inflow volume to the reservoir in month t; Qex(t) is the exogenous flow in month t; ∝ is the reduction coefficient of the total value of the exogenous flow; P(t) is the precipitated volume in month t; D is the reservoir demand, viewed as equal to the regularised flow with a 100% guarantee obtained for Scenario 2; and E(t) is the evaporated volume in month t.

The reservoir volume at the end of the month S(t+1) is subject to some limitations: It must be greater than or equal to the dead storage (Vmin) (below this volume, there will be a failure in meeting the demands), and it must be less than or equal to the maximum storage volume (Vmax). If it is greater, overflow will occur (Equations 2 and 3):

$$S(t+1) = \text{Vmín}, \text{if } S(t+1) < \text{Vmín} \tag{2}$$

$$S(t+1) = \text{Vmáx}, \text{if } S(t+1) > \text{Vmáx} \tag{3}$$

In the simulation of the reservoir operation, the SOP was considered, as it is the simplest operation rule and does not do rationing, i.e., all storage should be released to satisfy demands as much as possible (Maass et al., 1962).

The inflow data and the reservoir depth -area-volume curve were obtained from the Piancó-Piranhas-Açu Basin Plan (Agência Nacional de Águas, 2016a), and the precipitation and evaporation data were obtained from Agência Nacional de Águas (2017). Notably, the available inflow data include a historical series of 100 years, from 1913 to 2012, with an average annual flow of $68m^3/s$, maximum value of $436.68m^3/s$ in 1985 and minimum of $3.03m^3/s$ in 1919.

Reservoir simulation

Defining the zone boundaries (V1 and V2) in August that trigger the need to request water from PISF for the following year, as well as the rationing value for Zone 2, was performed using the GA, which simulates processes observed in natural evolution and, in this sense, starts with a randomly generated initial population and progresses to improve the solutions' fitness through iterations, implementing operators, including selection, crossover and mutation processes (Chang et al., 2010). The genetic algorithm application was developed in the R language and, using the GA package, is available in Scrucca (2013).

The objective function that was used comprised minimising the deficits in meeting demand with the lowest exogenous flow (Equation 4):

$$FO = min\{\sum_{t=1}^{N}\left[Qex(t)\right] + \sum_{t=1}^{N}\left[D(t) - R(t)\right]\} \tag{4}$$

in which N is the analysed period and R(t) is the volume of water released by the reservoir to meet the demand (D) at time t.

To use GA, we adopted mutation rates equal to 5% and population size and iterations equal to 200. This choice was based on previously performed simulations, in which it was observed that increasing the population size to values above 200 did not elicit significant gains for the optimisation, aside from lengthening processing time.

RESULTS

Diagnostic Scenarios 1 and 2

The Armando Ribeiro Gonçalves Dam presents, for the simulated period in the scenario without exogenous flow (Scenario 1), a regularised flow of $21m^3/s$ with a 100% guarantee (Figure 5). When compared with the present demand ($16.72\ m^3/s$), one can verify that the reservoir's regularisation capacity is higher than the estimated demand, indicating that the reservoir would not need the exogenous flow from PISF. However, it should be noted that the simulation considered the period from 1913 to 2012; thus, it did not include the long period of drought that occurred in the region between 2012 and 2018. During this period, the ARG needed to undergo rationing due to the suspension of non-priority uses (irrigation and aquaculture) to prevent the reservoir from collapsing (Brasil, 2014), and even with these suspensions and reductions, the reservoir in February 2018 reached $263.24hm^3$, equivalent to 10.9% of its storage capacity (Brasil, 2021).

In the scenario with a constant exogenous PISF flow of $1.97\ m^3/s$ (Scenario 2), the regularised flow presents an increase in relation to the previous curve, exactly equivalent to the value of the transposed flow, in such a way that the regularised flow with a 100% guarantee becomes $22.97m^3/s$ (Figure 5). It is interesting to note that this increase in flow was similar for all guarantees, i.e., for any guaranteed value, the difference in the regularised flow between Scenarios 1 and 2 was exactly the transposed flow.

To evaluate the impact of PISF waters' entry into the ARG on losses from evaporation and spillage, two situations were simulated for Scenarios 1 and 2: (i) the reservoir water use equals the current demands, and (ii) the water use equals the regularised flow with a 100% guarantee (Table 1). It can be observed that the addition of the constant exogenous flow to meet the current demand resulted in an increase in losses, mainly with respect to spilling. All the transposed flow was lost from spilling (88%) or evaporation (12%).

However, if the reservoir is used to its full capacity, i.e., all its regularisation capacity with a 100% guarantee was used, the introduction of the PISF flow, aside from resulting in an increase in availability, presents a reduction in the percentage of losses caused by the increase in the flow available to meet demands. In this way, the reduction in losses from evaporation and spillage results in a greater possibility of using the water that reaches the reservoir.

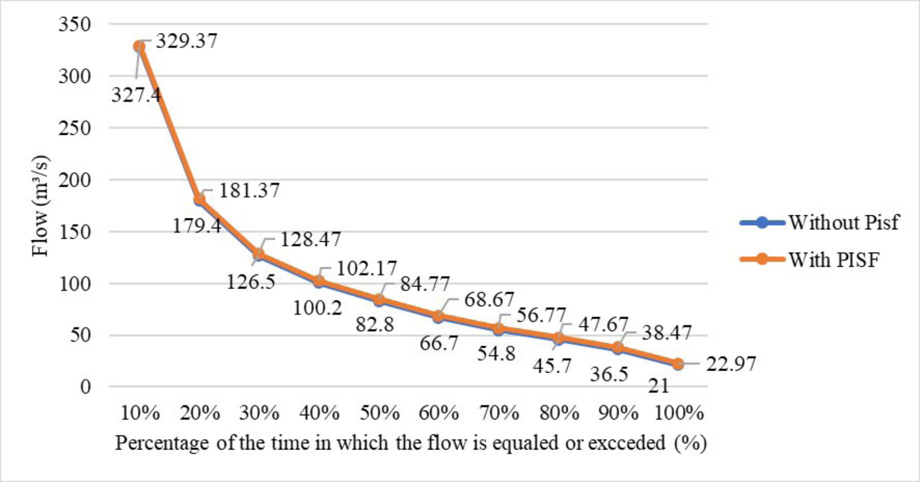

Figure 5. Reservoir regularisation curve with and without the exogenous PISF flow.

Table 1. Average annual reservoir outlet volumes for situations with and without exogenous flow.

Situation	Reservoir Flow Volume (10^7 m³/year)					
	Water spill	**%**	**Evaporation**	**%**	**Water Supply**	**%**
Scenario 1 with current demand (16.72 m³/s)	127.29	57.10	42.92	16.25	52.72	23.65
Scenario 1 with demand equal to the regularised flow with 100% guarantee (21.00 m³/s)	115.60	51.93	40.76	18.31	66.23	29.75
Scenario 2 with current demand (16.72 m³/s)	132.80	58.13	43.75	18.79	52.72	23.08
Scenario 2 with demand equal to the regularised flow with a 100% guarantee (22.97 m³/s)	115.60	50.52	40.76	17.81	72.44	31.66

Notably, in this study, the reservoir was evaluated in isolation, i.e., the water balance simulation process did not take into account the transit losses that may occur during the water-transfer process, nor the uses between the delivery portal and the ARG.

Operating scenarios

Looking to reduce the amount of water to be transferred from the PISF, the volume of water stored in the reservoir during August was used as an indicator of the reservoir's hydrological status when determining the need to request water from the PISF. This month was selected as an indicator because it is when state operators, such as Rio Grande do Norte, send to the federal operator their Annual Operating Plans containing the volumes requested for the following year.

Scenario 3 - Transference of water from PISF throughout the year

In Scenario 3, considering a constant exogenous flow during the entire year (January to December), the results indicated that the PISF's water only will be necessary, for the subsequent year, when the reservoir during August, is below 1,790 hm³, approximately 75% of its maximum storage capacity (Figure 6). When the reservoir is between 57% and 75% of its maximum capacity (Zone 2), the transferred flow will be 72% of 1.97 m³/s, i.e., the value of the PISF's transfer flow throughout the following year is equivalent to 1.42m³/s. In Zone 3, when the reservoir is at less than 57% of its storage capacity, the flow transferred from the PISF should be the total, i.e., 1.97m³/s.

Notably, for the 100-year historical series studied, 74% of the time the reservoir has remained in Zone 1, 15% in Zone 2 and 11% in Zone 3, equivalent to 74, 15 and 11 years, respectively.

The average annual volume of water transferred was 13.6 hm³, while in the diagnostic scenarios, in which the flow rate transferred is constant throughout the historical series of 100 years, the average annual volume of water transferred was 63 hm³. In other words, by defining hydrological criteria to trigger the need to transfer water between basins, average annual volume transferred decreased by approximately 80%.

As for losses from evaporation and spillage (Figure 7), despite the occurrence of a significant reduction in affluent volume in the reservoir when optimising transfers, the reduction in quantitative losses was small, at around 0.66%. This is because the average volume of water transferred is less than 3% of the average natural affluent volume; thus, the changes, even if significant in the transferred volumes, exert little influence on the reservoir losses.

Scenario 4 - Water transfer from PISF during the rainy season

Another question that this research aimed to answer was whether the period during which the water would be transferred influenced the reservoir operation's efficiency. Thus, the reservoir's hydrological conditions for triggering the transfer were optimised, assuming that the water transfer the following year would occur only during the rainy season, i.e., from January to June, but still

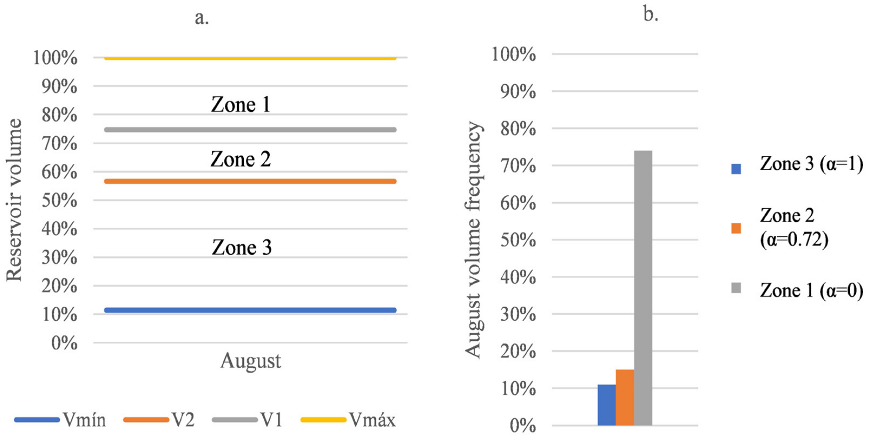

Figure 6. Reservoir activation volumes during August (a) and volume frequency in the study areas (b).

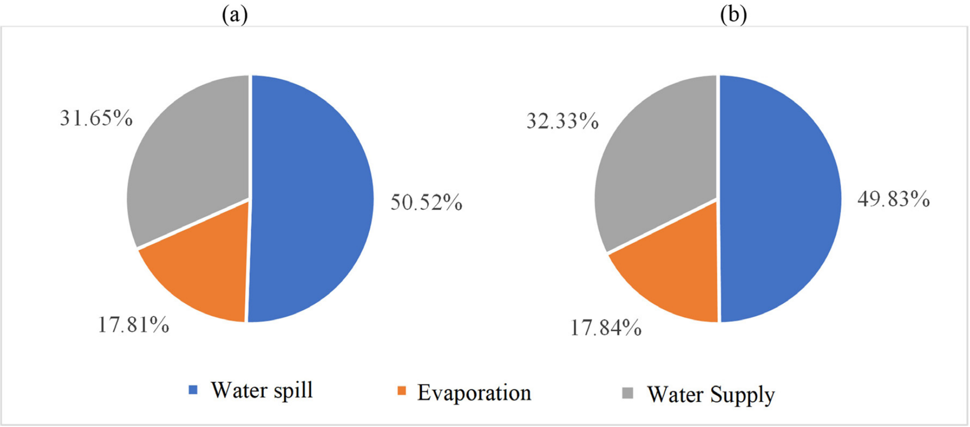

Figure 7. Percentage of reservoir outlet volumes considering constant (a) and optimised (b) year-round water transfer.

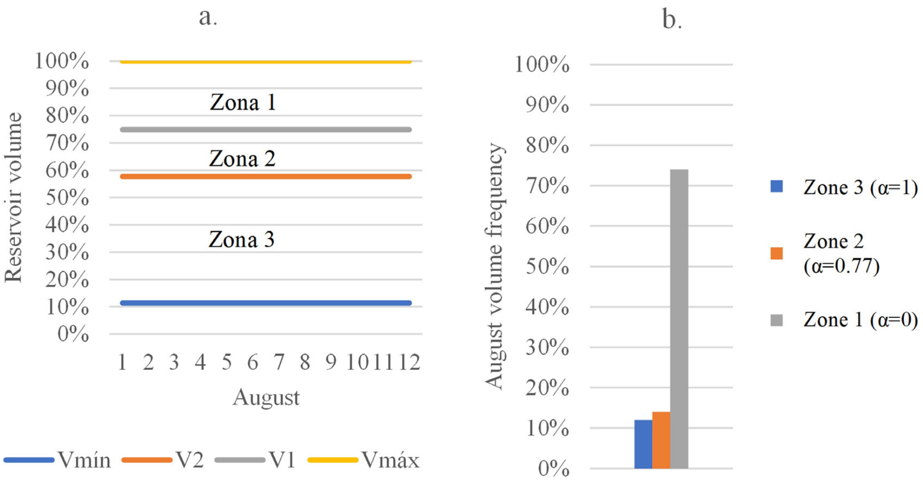

Figure 8. Reservoir activation volumes during August (a) and volume frequency in the study areas (b).

keeping the water volume stored during August as a trigger in the decision-making process regarding whether to request water transfers.

The reservoir's hydrological conditions for triggering water transfers (Figure 8) were very similar to the previous operating scenario, i.e., when the ARG dam is below 75% of its maximum storage capacity, equivalent to about 1,798 hm^3, the PISF transfer flow should be requested.

The limits of Zones 2 and 3 are also practically the same as those of Scenario 3. For the intermediate zone, the reservoir should be between 58% and 75% of its maximum storage capacity, and a coefficient of reduction in the transferred flow of 77% should be applied. Thus, the PISF transfer flow's total from January to June of the following year is equivalent to 3.06m^3/s. In Zone 3, the flow transferred from PISF should be the total – 3.97m^3/s – for a reservoir volume lower than 58%.

Regarding percentage of time that the reservoir remained in each zone, no significant differences were found with respect to the previous scenario, i.e., the ARG reservoir remained in Zone 1 74% of the time, 14% in Zone 2 and 12% in Zone 3 – equivalent to 74, 14 and 12 years, respectively – when analysing the 100-year series. In this scenario, the average annual volume of water transferred was 14.2 hm^3, a value 0.6 hm^3 per year above the previous scenario, representing a percentage increase of 4.45%.

The losses from evaporation and spillage, considering the total output volume (Figure 9), were similar to Scenario 3, presenting a percentage increase only in the evaporated volume and, consequently, a reduction in the supplied demand, i.e., analysing only the percentage, the concentrated volume transfers during the rainy season did not represent significant increases in losses, i.e., only 0.01%.

DISCUSSIONS

The results obtained from the diagnostic scenarios (Scenarios 1 and 2) indicated that the water transfer from the São Francisco River to the ARG reservoir resulted in an increase in water availability, represented in this study by the regularised flow with a 100% guarantee, which can provide the benefited region with a greater guarantee of the resource, reflecting on economic development. All the flow transferred from the PISF was reversed in the increase of water availability, with a reduction in the percentage of losses from spilling and evaporation, indicating more effective use of the water volume stored in the dam.

Notably, this increase in efficiency only occurs when the increase in the available flow is reverted into use, i.e., if demand actually increases. If the reservoir is operated under the current demands, the need for the exogenous flow of PISF becomes less visible, considering that a large part of the flow transferred by PISF that reaches the reservoir is not used, being lost mainly through spilling. However, the Hydric Resources Plan for the Piancó-Piranhas-Açu River Basin, in the tendency or critical scenario, presents an increase in demand for the ARG reservoir, reaching 21.42 m^3/s in 2032.

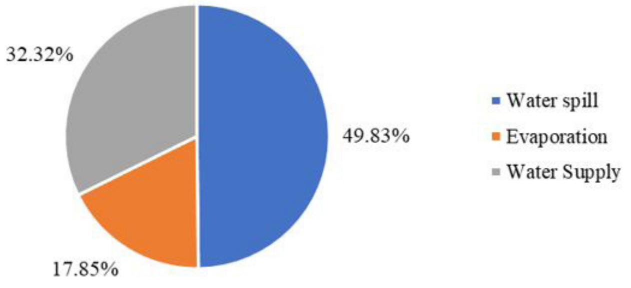

Figure 9. Percentage of the reservoir's output volumes while only considering water transfer during the rainy season.

Righetto & Guimarães Filho (2003) also observed an increase in demand resulting in a better application of the hydric resource in the ARG when using the exogenous flow available from the PISF. The increase in demand, i.e., a higher withdrawal flow from the reservoirs, elicits a reduction in losses from evaporation and water spillage. This better use of the reservoir is also known as water synergy (Farias et al., 2017; Silva et al., 2017).

In this sense, the need exists to think about projects and actions to promote the economy – such as incentives for agricultural and livestock production, creation of irrigated perimeters and installation of new industries – among other activities. Furthermore, the construction of complementary works is necessary, thereby enabling the feasibility of regional development from implementation of the PISF.

Thus, the existence of a guaranteed future inflow, the exogenous PISF flow, allows for adoption of more effective operational controls over the volume stored in the reservoirs so that it is not necessary to leave the reservoir full as a reserve for a prolonged drought, thereby reducing losses from evaporation and spillage under these new operating conditions.

Therefore, the PISF for the state of Rio Grande do Norte can achieve one of its objectives, which is to ensure water security and increase the amount of water available for human consumption and agricultural and industrial activities, enabling the existence of new productive activities and regional development.

However, to expand this reach, new structural engineering projects are necessary to complement the PISF, in addition to the existing ones. One of the current proposals for RN is the Seridó System, which would comprise more than 330 kilometres of water mains, interconnecting the large reservoirs with the objective of transferring water with a guarantee to 24 municipalities, supplying approximately 280,000 people from the region's municipalities. This system would add to the 14 existing large pipelines in the state of Rio Grande do Norte (Trolei & Silva, 2018), five of which use the Armando Ribeiro Gonçalves Dam. The system attend about 30 municipal seats and 305,000 inhabitants.

Therefore, even when demand increases, it is evident from the results obtained in the operational scenarios that it is not always necessary to transfer water from the São Francisco River to the RN. During rainy years, when reservoirs contain high volumes of stored water, the transfer is unnecessary, or there is no need to transfer the entire volume. An average annual reduction in the total volume transferred was observed to be around 78%, along with a reduction in losses from evaporation and spillage of around 0.66%.

The difference in the volume to be transferred influences transfer costs because according to the ANA resolution (Brasil, 2017), the PISF tariff will be of the binomial type, comprising availability and consumption tariffs. The availability tariff is a fixed value arising from the PISF operation costs and charged regardless of water pumping, and the consumption tariff is charged proportionally to the volume of water supplied to the states at the delivery points.

Considering only the consumption tariff in regard to the values defined in Agência Nacional de Águas (Brasil, 2017), for the year 2021, in analysing the State's costs over 10 years as an example, it has been verified that in Scenario 2, with the PISF transfer flow constant, the State's cost would be approximately US$57,480,000.00, while in Scenario 3, with water transfer only when necessary, the cost would be US$14,510,000.00. These results highlight the importance of implementing a rational management policy that considers both local hydrological states, inflow expectations and the pumping cost of the PISF, as well as natural losses in the system.

When comparing Scenario 3, year-round transfer, with Scenario 4, transfer only during the rainy season, small differences were found, both in reservoir volumes that trigger requests for water from the PISF, as well as in volumes to be transferred and in losses due to evaporation and spillage, indicating that the decision maker can consider other factors when deciding whether to request a transfer distributed over time or concentrated during the rainy season. One aspect that can be considered when choosing between Scenarios 3 and 4 is the transit losses in the channels, either from evaporation or uncontrolled withdrawals. Notably, transit losses along rivers and channels can be significant (Brito et al., 2019; Farias, et al., 2017).

CONCLUSIONS

The present study presented the definition of technical criteria for the operation of water reservoirs in the context of water transfer between watersheds, using the Armando Ribeiro Gonçalves reservoir (ARG), one of the receiving reservoirs of the PISF water in the state of Rio Grande do Norte, Brazil, as a test case.

Water transfer from the São Francisco River to the ARG reservoir elicits an increase in the regularised flow rate with a 100% guarantee, equal in value to the transposed flow rate.

The increase in exogenous flow aligned with the increase in service demand elicit greater reservoir efficiency and reduced percentage losses from spilling and evaporation.

Optimisation of transferred volumes, based on the ARG's hydrological state during August, indicated that the State would not need to request PISF water annually, with transfers necessary during only 26% of the years examined, resulting in a reduction in the average annual volume transferred of 78%, consequently lowering the State's costs with the PISF.

Volume transfer period (throughout the year or only during the rainy season) did not make a significant difference in total annual volume transfers and the percentage of losses from evaporation and spillage, making it necessary to analyse other factors, such as the cost of transferring the water, transportation time and losses from decision making.

The results demonstrate that using hydrological conditions to define when and how much water to transfer is extremely important in managing water resources, as this method increases reservoir efficiency, reduces volumes transferred and, consequently, lowers costs, thereby providing better service for populations and aiding managers and responsible agencies' decision-making processes.

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