Edição especial – VI Winotec

ISSN 1808-8546 (ONLINE) 1808-3765 (CD-ROM)

IMPACTO DA EVAPORAÇÃO NA DISPONIBILIDADE HÍDRICA DO RESERVATÓRIO FOGAREIRO FRENTE ÀS MUDANÇAS CLIMÁTICAS: UMA ABORDAGEM COM O MODELO VYELAS

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1 RESUMO

As mudanças climáticas e o uso desordenado do solo afetam os recursos hídricos no semiárido, e as simulações são cruciais para prever o impacto na disponibilidade de água em açudes. Nesse sentido, o objetivo do estudo foi avaliar o impacto da evaporação na disponibilidade hídrica do açude Fogareiro em cenário de mudança climática utilizando o modelo VYELAS. O *output* do modelo forneceu vazões regularizadas como Q_{90}, Q_{95} e Q_{98}, que para o cenário atual foram iguais a 23,12 hm³.ano^{-1}, 19,56 hm³.ano^{-1} e 16,84 hm³.ano^{-1}, respectivamente, enquanto que o cenário futuro apresentou uma redução de 0,67% a 4,11% nas vazões de garantia em função do acréscimo de 4% na evaporação média do período seco. Esse cenário mostrou que o incremento na taxa de evaporação acarretaria na redução do abastecimento de água de aproximadamente 5.379 habitantes.ano^{-1} e na diminuição da irrigação de cerca de 34 hectares de milho.ano^{-1}. Conclui-se que as mudanças climáticas, refletidas no aumento da evaporação, têm um impacto direto e significativo na disponibilidade hídrica do açude Fogareiro.

Palavras-chave: balanço hídrico, semiárido, gestão hídrica

FEITOSA, J. N. A.; SOUSA, J. S. F. O.; SILVA NETO, T. A.; LIMA, G. D.; LIMA, J. B. C.
ANALYSIS OF INCREASED EVAPORATION ON WATER AVAILABILITY IN THE FOGAREIRO RESERVOIR, CEARÁ

Recebido em 03/12/2024 e aprovado para publicação em 12/12/2024
DOI: http://dx.doi.org/10.15809/irriga.2024v29p90-99

2 ABSTRACT

Climate change and unregulated land use impact water resources in semiarid regions, making simulations crucial for predicting their effects on water availability in reservoirs. In this context, the present study aimed to assess the impact of evaporation on the water availability of the Fogareiro Reservoir under a climate change scenario via the VYELAS model. The model output provided regulated flow rates, such as Q_{90}, Q_{95}, and Q_{98}, which, for the current scenario, were 23.12 $hm^3.year^{-1}$, 19.56 $hm^3.year^{-1}$, and 16.84 $hm^3.year^{-1}$, respectively. In contrast, the future scenario indicated a 0.67% to 4.11% reduction in guaranteed flows due to a 4% increase in average evaporation during the dry period. This scenario demonstrated that an increase in evaporation rates would lead to a decrease in the water supply for approximately 5,379 inhabitants per year and a reduction in the irrigation capacity of approximately 34 hectares of maize per year. It is concluded that climate change, reflected in increased evaporation rates, has a direct and significant effect on the water availability of the Fogareiro Reservoir.

Keywords: VYELAS, evaporation, water balance

3 INTRODUCTION

Climate change and disordered land use in the semiarid region of Brazil directly impact water quality, runoff variations and evapotranspiration, leading to frequent flash floods and rising sea levels and requiring water resource management and mitigation strategies (Abbas; Zhao; Wang, 2022; Nascimento; Borges; Melo, 2023).

From this perspective, carrying out simulations is seen as a fundamental study to assess the impact of climate change on water availability in reservoirs, as it makes it possible to predict the future behavior of water systems in different scenarios, such as rising temperatures and changes in rainfall (Gil *et al*., 2020; IPCC, 2021; Nascimento; Borges; Melo, 2023). This assessment from the perspective of water availability is particularly important in the semiarid region of Brazil, where the water supply depends directly on reservoirs (Rodrigues *et al*., 2024), which are already subject to a decrease in water quality and quantity due to silting (Araújo *et al*., 2023; Medeiros; Sivapalan, 2020).

Studies carried out in the northeastern region of Brazil indicate that there is no clear temporal trend in evaporation values, with both increases and reductions detected (Rodrigues *et al*., 2021). This suggests that local particularities play a determining role in this behavior.

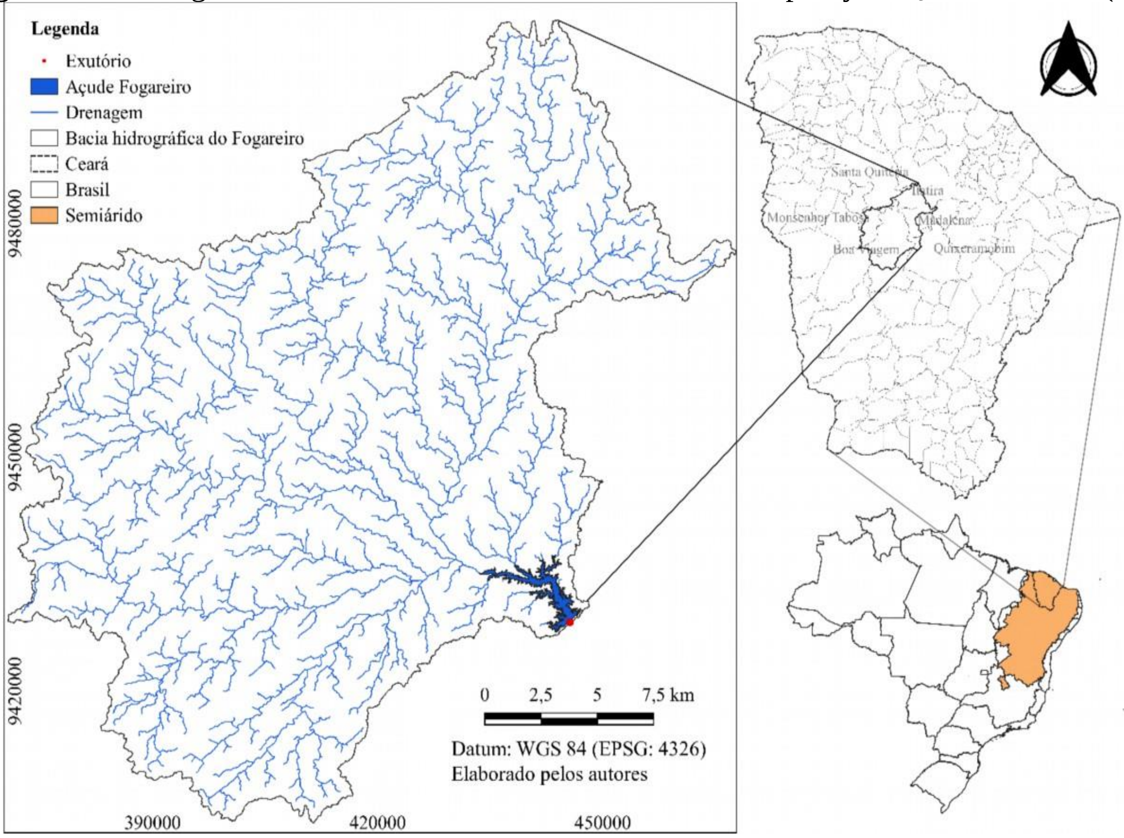
The scenario becomes even more challenging when we incorporate the uncertainties of climate change, since global circulation models do not present a consensus on the forecast of trends (Rodrigues *et al*., 2024).

In this context, the present study aims to evaluate the impact of evaporation on the water availability of the Fogareiro reservoir, Ceará, in the face of climate change (increased evaporation rate) through the VYELAS model.

4 MATERIALS AND METHODS

The study was carried out at the Fogareiro Reservoir, a strategic reservoir monitored by the Ceará Water Resources Management Company (COGERH), which is part of the Banabuiú system and is located in the municipality of Quixeramobim (Figure 1). This reservoir has a hot semiarid tropical climate, with average annual rainfall of approximately 700 mm and average temperatures ranging from 26°C to 28°C, with rainfall concentrated between the months of February and April (Government of the State of Ceará, 2017). According to the Ceará Foundation of Meteorology and Water Resources (FUNCEME, 2024), the reservoir has a hydrographic basin of approximately 5 thousand km² and a capacity of 118 hm³ (COGERH, 2024). The main uses of the reservoir are for human supply (0.35 Ls $^{-1}$) and irrigation (0.29 Ls $^{-1}$), as presented in the Banabuiú Region Diagnosis document.

Figure 1. The Fogareiro reservoir basin **is** located in the municipality of Quixeramobim (CE)**.**



A yield model was used to calculate water availability. Elasticity - VYELAS (Araújo; Güntner; Bronstert, 2006), which calculates the water balance in annual steps on the basis of the following variables: average annual inflow; coefficient of variation of the inflow (Equation 1); reservoir shape coefficient (Equation 2); evaporation in the dry period (calculated via the Penman method); storage capacity (maximum reservoir capacity); minimum operational volume (considered 10% of the maximum reservoir capacity); volume at the beginning of the simulation (considered the average volume of the first 5 years studied); maximum values (considered equal to the average annual inflow); minimum (the lowest possible value) of simulated regularizable flows; number of simulated regularizable flows; and number of simulations of the stochastic procedure.

$$C_v = \frac{S}{\bar{x}} \quad (1)$$

$$\alpha = \frac{V}{h^3} \quad (2)$$

where Cv is the coefficient of variation of the influent flow; S is the standard deviation of the influent volume (hm³); $\bar{x}$ is the average of the influent volume (hm³); α is the reservoir shape coefficient (dimensionless); V is the reservoir volume (m³); and h is the reservoir elevation measured from the bottom (m).

For the base scenario, data on reservoir flows and volumes obtained from the Ceará Foundation for Meteorology and Water Resources (FUNCEME. 2024) for the years from 2004--2024 were used, whereas evaporation was calculated via the Penman method (1948) via data from Quixeramobim Station for the last 10 years. For the simulated scenario (perspective of increased evaporation), the same input data were used, except for evaporation **during** the dry period (**June–December), which was** considered 4% **greater** than **the** observed value. This percentage was defined on the basis of the studies by Fernandes *et al*. (2017), who assessed the implications of climate change on the water availability of large reservoirs in the semiarid region for the middle and end of the 21st century.

The scenarios were compared via regularization flows for different guarantees (Q_{90}, Q_{95} and Q_{98}), since these are the reference flows established in CONERH Resolution No. 08/2022 (Teixeira; Campelo, 2022) for the state of Ceará.

5 RESULTS AND DISCUSSION

The analysis of precipitation and evaporation data during the dry period (Table 1) revealed significant interannual variability over the 10 years evaluated (2008--2016 and 2019). The annual precipitation varied between 270.2 mm (2012) and 1,107.5 mm (2009), highlighting the irregularity of the rainfall regime characteristics of semiarid regions. The evaporation values ranged between 1,404.94 mm.year^{-1} (2011) and 1,578.81 mm.year^{-1} (2012), with an average of 1,495.58 mm.year^{-1} over the analyzed period. The increase in evaporation in years of lower precipitation suggests an amplified effect of drought on the reservoir's water availability, which can significantly compromise regularized flows.

Table 1. Total annual precipitation and evaporation in the dry season (2008--2019)

Ano	P(mm)	E(mm.ano^{-1})	Ano	P(mm)	E(mm.ano^{-1})
2008	723,3	1.558,16	2013	682,7	1.464,70
2009	1.107,5	1.450,90	2014	401,6	1.505,67
2010	706,4	1.503,83	2015	421,7	1.541,76
2011	1021,8	1.404,94	2016	394,6	1.493,19
2012	270,2	1.578,81	2019	664,9	1.453,80

The study by Rodrigues *et al*. (2021) highlighted that evaporation is a critical factor in water resource management in semiarid regions, such as Northeast Brazil. The authors noted that evaporation can represent a significant loss in the water balance of reservoirs, especially in climate change scenarios that tend to intensify this process. The analysis of Table 1 corroborates this concern, showing that, even in years with high precipitation, high evaporation rates can substantially reduce water availability. The reduction in water availability is not restricted to the semiarid region of Brazil. When analyzing the impacts of climate change in a basin located in the state of São Paulo, Gonzalez *et al*. (2023) reported that meteorological parameters significantly influence the water supply. The results highlight the need for adaptation strategies and integrated planning to ensure water sustainability in the region.

These results support the need for adaptive water management strategies that consider not only precipitation variability but also the intensification of evaporation under climate change scenarios. Rodrigues *et al.* (2024), analyzing the potential effects of climate change on water resources in northeastern Brazil, reported that by the end of the century, evaporation rates during the dry season could increase by between 2% and 6% in some scenarios, whereas in others, evaporation rates could decrease by 2%. These variations could result in a reduction of up to 80% in the capacity of the reservoirs to supply water with high reliability. Notably, the Fogareiro Reservoir already faces significant challenges due to the high variability in annual precipitation and high evaporation rates, according to the projections of Rodrigues *et al*. (2024) suggested that these challenges could intensify in the future, especially if evaporation rates increase, as predicted in some scenarios. This could further compromise the water availability of the reservoir, affecting the water supply in the region.

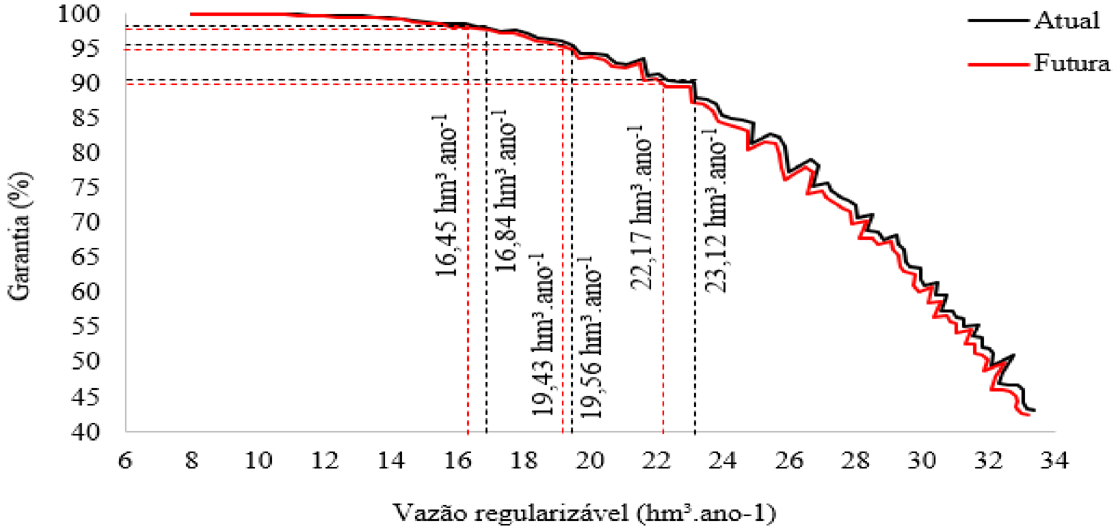
Table 2 presents the input data *for* the VYELAS model, whose average inflow, obtained from the historical series (2004--2024), corresponded to 47.78 $hm^3.year^{-1}$, with a coefficient of variation of 93% and a parameter α of 5565. These values *output* the regularization flows for different guarantees, with Q_{90}, Q_{95} and $Q_{98\ being}$ equal to 23.12 $hm^3.year^{-1}$, 19.56 $hm^3.year^{-1}$ and 16.84 $hm^3.year^{-1}$, respectively.

Table 2. Input data of the Fogareiro reservoir for the VYELAS model

Input data (*Input*)	
Average annual inflow ($hm^3.year^{-1}$)	47.78
Coefficient of variation of inflow (C_v)	0.93
Reservoir shape coefficient (α)	5565
Evaporation in the dry period ($m.year^{-1}$)	1.5
Storage capacity (hm^3)	118
Minimum operating volume (hm^3)	11.8
Volume at the start of the simulation (hm^3)	81.03
Number of simulated regularizable flows	100
Minimum yield of simulated regularizable flows ($hm^3.year^{-1}$)	8.0
Maximum yield of simulated regularizable flows ($hm^3.year^{-1}$)	47.78
Number of simulations of the stochastic procedure	10,000

To analyze the impacts of climate change on water availability, the same input data were used, except for evaporation **during** the dry period, which corresponded to 1.56 $m.year^{-1}$ (an increase of 4%). This increase implied a reduction of 0.67% to 4.11% in the regularization flows, with Q_{90}, Q_{95} and Q_{98} being equal to 22.17 $hm^3.year^{-1}$, 19.43 $hm^3.year^{-1}$ and 16.45 $hm^3.year^{-1}$, respectively. Figure 2 graphically shows the reduction in water availability, in which it can be noted that for greater guarantees, the variation in water availability between the scenarios is smaller, being more pronounced for lower guarantees. This finding indicates that the influence of evaporation is more significant in the context of low water reliability (Rodrigues, 2023).

Figure 2. Water availability as a function of the annual reliability level of the reservoir.



The curves represent an evaporation rate for the average of the last 10 years and for future climate change in the middle to the end of the 21st century.

Considering that Q_{98} is the high-guarantee flow rate, which is commonly associated with human supply, the results indicate that if this scenario materializes, there will be a reduction in the water supply sufficient to supply approximately 5,379 inhabitants.year $^{-1}$, considering a per capita consumption of 200 L.inhabitants.day $^{-1}$.

The scenario becomes more complex when we talk about irrigated agriculture, since Q_{80} is related to the irrigation of agricultural crops. Thus, an increase in the evaporation rate would result in a reduction of 34 hectares of corn.year $^{-1}$, considering that the crop requires 600 mm.year $^{-1}$ (Pegorare *et al*.). 2009). This decrease in the irrigated area may compromise the food supply to the population.

Water loss through evaporation in reservoirs is a common phenomenon in semiarid environments (Medeiros; Sivapalan, 2020), making efficient water resource management measures necessary to minimize losses and increase reservoir reliability (Brazil; Medeiros, 2020).

Importantly, evaporation in the dry period equal to 1.5m.year^{-1} may be an overestimated value since the method used was Penman (Feitosa; Araújo; Barros, 2021). Despite this, it is the most widely used and reliable methodology for estimating evaporation in reservoirs (Althoff; Rodrigues; Silva, 2019; Vieira *et al*., 2016).

Finally, it is worth noting that the reduction in water availability at the Fogareiro reservoir may be greater than 4.11% when considering siltation. This phenomenon has been intensified by land use processes, which contribute to degrading this resource and increasing sediment production (Duraes; Mello; Beskow, 2016; Feitosa; Araújo, 2016), which are deposited in reservoirs, resulting in a decrease in water supply (Araújo, 2003; Araújo; Landwehr; Alencar, 2023; Gil; Araújo; Montenegro, 2020). This situation represents a paradox in relation to the main objective of reservoirs, which is to guarantee water supply (Medeiros; Sivapalan, 2020).

6 CONCLUSIONS

It is concluded that climate change, reflected in increased evaporation, has a direct and significant effect on the water availability of the Fogareiro Reservoir. The analysis with the VYELAS model revealed that a 4% increase in the evaporation rate during the dry period resulted in a decrease in the regularization flows (Q_{90}, Q_{95} and Q_{98}) of up to 4.11%, which compromised the water supply.

This scenario highlights the need for adaptation measures and sustainable management of water resources to mitigate the effects of climate variability, especially in regions where dependence on reservoirs is essential for water supply and local economic activities. Therefore, it is necessary for the entire society (government, researchers and local communities) to work together to formulate mitigating measures. To ensure water security in the region, it is important to diversify supply sources, monitor water levels and use available resources wisely.

7 ACKNOWLEDGMENTS

Hydrosedimentological Research Group of the Semiarid Region (HIDROSED) and the Postgraduate Program in Agricultural Engineering at the Federal University of Ceará for the structure provided to carry out this work, in addition to the Coordination for the Improvement of Higher Education Personnel (CAPES).

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