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Eutrophication risk assessment of a large reservoir in the Brazilian semiarid region under climate change scenarios

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Abstract: The present study assesses the risk of eutrophication of a large semiarid reservoir under SSP2-4.5 and SSP5-8.5 scenarios for three future periods and different conditions of influent total phosphorus (TP) concentration and reservoir withdrawal. An integrated approach coupling climate, hydrological and water quality models was proposed for forecasting the climate change impacts on the trophic condition of the reservoir. The projected TP concentrations were organized as probability-based cumulative distribution functions to quantify the risk of eutrophication. The results indicated changes of eutrophication status in the three future periods, with the end of the 21st century experiencing the highest impacts on water quality. On the other hand, major reductions both in the inlet TP concentration and the reservoir withdrawal are necessary to significantly improve the trophic status and minimize the risk of eutrophication. The results also showed that the dry period is more susceptible to eutrophication than the rainy period, suggesting that tropical semiarid reservoirs are more vulnerable to eutrophication under climate change than reservoirs in other regions of the world. The proposed approach and model results are important to better understand the impact of climate change on reservoir water quality and improve water resources management in tropical semiarid regions.

Key words: Climate change, eutrophication, risk analysis, tropical semiarid region, water quality.

INTRODUCTION

Projected changes of future climate indicate potential changes in the hydrological cycle, strongly impacting global water resources (Kundzewicz et al. 2018). Extreme meteorological and hydrological events can be expected in future, resulting in more frequent droughts and floods posing more uncertainty and risk in water resources management (Shrestha et al. 2017, Raulino et al. 2021). There is evidence that the water quality of the reservoirs is influenced by various climatic mechanisms (Hamilton et al. 2016, Carvalho et al. 2022). Therefore, climate change can impact not only the quantitative aspects, but also the qualitative aspects of reservoirs, affecting the input nutrient loads and the internal concentration of pollutants (Bucak et al. 2018, Me et al. 2018). On the other hand, excessive nutrient levels in water bodies can cause eutrophication, which constitutes one of the major environmental problems faced by society (Pacheco & Neto 2017, Rocha & Neto 2022b, Wiegand et al. 2021). Phosphorus has been considered as the primary limiting eutrophication factor in reservoirs and, as a consequence, many studies have taken the total phosphorus (TP) concentration in the reservoirs as a water quality state variable (Araújo et al. 2021, Nazari-Sharabian et al. 2019a, Lira et al. 2020, Moura et al. 2020, Rocha & Neto 2022a, Neto et al. 2022).

Integrated approaches coupling climate, hydrological and water quality models have been used to investigate the potential impacts of climate change on the water quality of reservoirs (Thorne & Fenner 2011). A commonly applied methodology consists of projecting future temperature and precipitation data using General Circulation Models (GCMs), driven by Representative Concentration Pathways (RCPs) (more recently Shared Socioeconomic Pathways - SSPs), which serve as inputs for a hydrological model. Then, the outputs of the hydrological model are manually fed into water quality models in order to predict the future TP concentrations in the reservoirs. From future TP concentrations, it is possible to classify the reservoir according to its trophic state. Several steady-state and unsteady-state solutions of the complete-mix model of Vollenweider (Vollenweider 1968) have been used to estimate the TP concentration in lakes and reservoirs around the world (Nielsen et al. 2013, Molina-Navarro et al. 2014, Lira et al. 2020, Rocha & Neto 2021).

One of the major challenges regarding the analysis of the impacts of climate change on both the quantitative and qualitative aspects of water resources is the uncertainty in the various stages of coupled models. Strong divergences in future concentration of nutrients in reservoirs pose a major challenge for water quality management under climate change scenarios. Uncertainties can generally be categorized as either epistemic or random (Tung 2018). The former is a consequence of the variability of the climatic system and the hydrological cycle, while the latter is related to the parameters, inputs and structure of the model (Gupta & Govindaraju 2018). Generally, a consensus has been reached among researchers that the climate change model and downscaling methodology are usually the largest source of uncertainty when combining climate, hydrological and water quality models (Chang et al. 2015). Furthermore, uncertainties due to the model parameters and structure are found to be relatively less relevant if the variations from different climate model outputs is considered (Chang et al. 2015).

Many authors have highlighted that the ensemble climate models should be employed to provide a more robust approach to evaluate the impacts of climate change on water quality (Bucak et al. 2018, Couture et al. 2018, Deb et al. 2018, Marhaento et al. 2018). However, uncertainties in the outputs of water quality state variables can create ranges of values that make the elaboration and application of strategies to combat the negative impacts of climate change more complex. In these situations, working with the risks generated by global uncertainties, that is, the final outputs of the water quality state variable, can be useful to provide more appropriate information for decision makers. In this sense, one of the alternatives is to reorganize the outputs of the ensemble of the climate models as probability-based cumulative distribution functions (CDFs) to quantify the risk of the water system. Some studies that have investigated the impacts of climate change on the water quality of the reservoirs have successfully used this methodology, generating more adequate information for water quality management decision-making (Thorne & Fenner 2011, Chang et al. 2015, Shalby et al. 2020). This approach is even more relevant and required for regions where future climate projections experience divergences in climatic (e.g. precipitation) and hydrological (e.g. streamflow) outputs, both of magnitude (absolute value of the relative change) and of signal (increase or decrease), which make risk management of the water system even more complex, as observed in the case of the Brazilian semiarid region.

The main objectives of this research were to: (1) predict future TP concentrations in the Orós reservoir, located in the State of Ceará, Brazil, for three future periods by using an integrated approach coupling five climate models, a hydrological model, a water quality model and two SSPs-RCPs; (2) quantify the risk of reservoir eutrophication considering the outputs of the water quality model using probability-based CDFs; (3) analyze the seasonality of the TP concentration in the reservoir; and (4) assess the effects of reductions in the influent TP concentration and the total reservoir withdrawals on the TP concentration in the reservoir. In the authors' view, this is an unprecedented study for tropical semiarid regions.

MATERIALS AND METHODS

Study area

The study area is the Upper Jaguaribe sub-basin, located in the State of Ceará, Brazil, as shown schematically in Fig. 1. This watershed covers an area of 24,639 km², more than 80 % of which is on shallow soil on a crystalline basement. The region has a warm semiarid climate, with an average monthly temperature always above 18ºC, average annual rainfall of 700 mm and strong annual average evaporation of 2300 mm (Malveira et al. 2012). The sub-basin is marked by strong spatial and temporal variability of precipitation, in which a large part of the rainfall (about 75%) is concentrated between February and May (Cavalcanti et al. 2009, Palharini & Vila 2017).

The Orós is the largest reservoir (1,940 hm³ capacity) in the Upper Jaguaribe sub-basin and the second largest in the state (Fig. 1). This reservoir was built in 1961 with the purpose of perennializing its main tributary (Jaguaribe river) to guarantee human, agricultural and industrial water uses along the river and the Metropolitan region of Fortaleza, the state capital (Lopes et al. 2014). The monitoring of the streamflow towards the Orós reservoir is done through a flow station (control section) in the Jaguaribe river, which is managed by the National Water Agency and Sanitation - ANA. The land use in the catchment area is strongly influenced by anthropic action, such as agriculture and livestock farming activities (COGERH 2011).

SMAP model

The hydrological model used in this study is a conceptual and lumped model called Soil Moisture Account Procedure (SMAP), which has been developed by Lopes et al. (1982). The SMAP model consists of two linear reservoirs (subsurface and groundwater) that are updated over time (hourly, daily or monthly) through water balance equations, including surface runoff, precipitation, evapotranspiration, infiltration and base flow. It is a simple application model, in addition to being particularly suitable for the present study for two reasons: (1) the combined approach proposed in this study did not consider changes in land use, which were not relevant during the calibration and validation periods, and (2) the region is characterized by scarcity of hydrological data for the proper application of process-based models. Note that this will also be discussed ahead. It is also important to mention that the SMAP

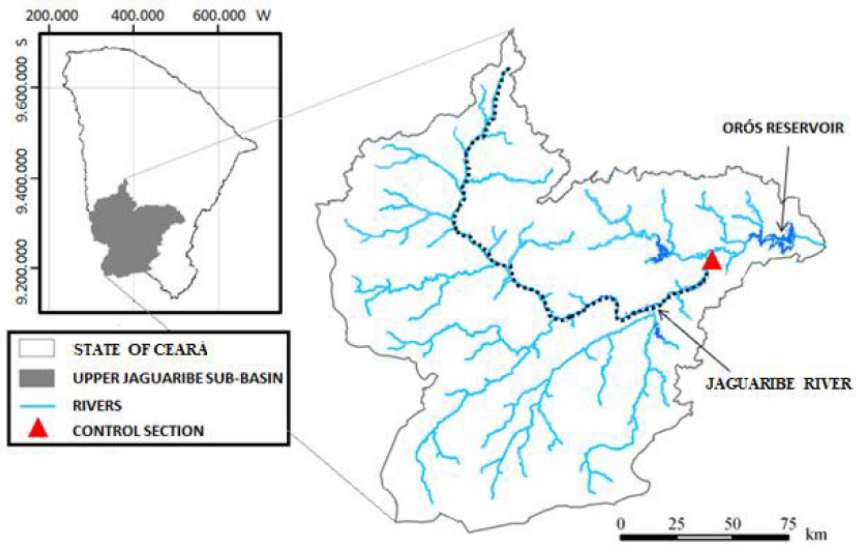

Figure 1. Location of the Upper Jaguaribe sub-basin and the Orós reservoir, State of Ceará, Brazilian semiarid region.

model has been successfully applied in many Brazilian basins (Block et al. 2009, Kwon et al. 2012, Gondim et al. 2018).

The Nash-Sutcliffe efficiency (NS) was used as an objective function to assess SMAP performance. The Pearson's correlation coefficient (r) and determination coefficient (R^2) were used as complementary metrics.

This study used the SMAP monthly time step, with calibration and validation periods 2005-2007 and 2008-2010, respectively. The streamflow data were obtained from the National Water and Sanitation Agency - ANA (http://www.snirh.gov.br/). Precipitation data were obtained from the Ceará Foundation for Meteorology and Water Resources - FUNCEME (http://www.funceme.br/). The average monthly rainfall over the sub-basin was calculated using the Thiessen polygon method. The climatological values of potential evapotranspiration were obtained from the National Institute of Meteorology - INMET (http://www.inmet.gov.br/), which is the standard procedure adopted in hydrological studies in the region (Kwon et al. 2012).

Climate change scenarios

Five different GCMs (BCC-CSM2-MR, CanESM5, IPSL-CM6A-LR, MIROC6 and MRI-ESM2-0) were used to carry out this study. The GCM runs performed through the Coupled Model Intercomparison Project Phase 6 (CMIP6) (https://esgf-node.llnl.gov/search/cmip6/). The five GCMs were driven by SSP2-4.5 and SSP5-8.5 scenarios in order to obtain future temperature and precipitation data. The projections of the climatic variables (precipitation and temperature) were interpolated from GCMs grids to the basin area. The bias present in the future monthly precipitation and temperature data, forecasted by the GCMs, were statistically corrected through the gamma distribution (Block et al. 2009). The bias correction used observational data from FUNCEME (https://www.funceme.br) for 1974-1999. The projected maximum, minimum and average temperatures were used as inputs to the Hargreaves-Samani (HS) method to generate future data of potential evapotranspiration over the sub-basin. Finally, the projected precipitation and evapotranspiration data were used to run the

SMAP model and generate the streamflows for the Orós reservoir for three future periods: 2015-2044, 2045-2074 and 2075-2100.

Water balance and Total Phosphorus (TP) model

The consideration of the variation in the stored volume is essential to predict the TP concentration in reservoirs located in the semiarid climate, since these water bodies experience strong interannual and seasonal variations in their volume, in addition to the effect of periodic droughts. In this sense, the future projection of the stored volume was also carried out through the following water balance equation (Campos et al. 2016):

$$V_{i+1} = V_i + (Q_{a,i} - Q_{90,i} - EL_i A_i - S_i)(t_{i+1} - t_i) \tag{1}$$

where t_{i+1} (T) and t_i (T) refer to the present and past times, respectively, $V(L^3)$ represents the water volume in the reservoir, Q_a (L^3T^{-1}) denotes streamflow, Q_{90} (L^3T^{-1}) denotes regularized streamflow or total reservoir withdrawals with 90% reliability, EL (LT^{-1}) is the average reservoir water losses (evaporation less precipitation from the lake surface), A (L^2) represents the surface area of lake, and S (L^3T^{-1}) is the spilled volume. The Depth-Area-Volume (DAV) curve was obtained from the Ceará State Water Resources Management Company - COGERH (http://www.hidro.ce.gov.br). The average monthly water losses of Orós reservoir were obtained from a detailed study on reservoirs in the Brazilian semiarid region conducted by the National Water Agency - ANA (ANA 2017).

The impacts of climate change on the water quality of the Orós reservoir were evaluated by adapting the complete-mix model of Vollenweider (Vollenweider 1968), in which an unsteady-state discrete solution was derived:

$$TP_{i+1} = TP_i \frac{V_i}{V_{i+1}} + \frac{Q_{a,i}c_{a,i} - Q_{90,i}TP_i - k_i TP_i V_i}{V_{i+1}} \tag{2}$$

where TP is the average total phosphorus concentration in the reservoir (ML^{-3}), $c_{a,i}$ is the influent TP concentration (ML^{-3}) and k is the settling loss coefficient of TP (T^{-1}).

The calculation of k-values for tropical semiarid reservoirs is performed by using the following expression (Tone & Neto 2020):

$$k = \frac{4}{\sqrt{\tau_w}} \tag{3}$$

where τ_w is the hydraulic residence time (T), representing the time necessary for the reservoir water to be renewed, which is defined here as the ratio between the reservoir's volume (L^3) and the inflow (L^3T^{-1}). This simple approach to estimate τ_w demonstrates a good accuracy for relatively well mixed lakes (Pilotti et al. 2014). Consistently, Brazilian semiarid reservoirs present very weak stratification contrasts from top to bottom (up to about 1-4ºC), that are destroyed on a daily cycle (Neto 2019, Mesquita et al. 2020). It is also important to observe that Eq. (3) was adjusted and validated by Tone & Neto (2020) for a wide range of Brazilian semiarid reservoirs. Additionally, it was also validated by Lima et al. (2018) and Araújo et al. (2021) for reservoirs located specifically in the state of Ceará.

Due to the lack of monitoring of the influent TP concentration, the correlation proposed by Rocha & Neto (2020) was used [Eq. (4)], which relates the average influent TP concentration and the streamflow:

$$c_{a,i} = 4.46 Q_a^{-0.964} (R^2 = 0.92) \tag{4}$$

Based on future projections of average TP concentrations, the reservoir was classified according to the following trophic levels, based on the TP concentrations adopted by COGERH (Toledo et al. 1983, Klippel et al. 2020): oligotrophic ≤ 0.026 mg/L, 0.027 mg/L ≤ mesotrophic ≤ 0.052 mg/L, 0.053 mg/L ≤ eutrophic ≤ 0.211 mg/L and hypereutrophic > 0.211 mg/L.

Eutrophication risk assessment

In order to provide more convenient information for decision makers, taking into account the uncertainties inherent in the projections of future climate change impacts on reservoir water quality, the average annual TP concentrations projected from the integrated approach coupling climatic, hydrological and water quality models, were organized as probability-based cumulative distribution functions (CDFs) to identify the probability exceeding the specific threshold values. Hence, three expressions [Eqs. (5), (6) and (7)] can be defined to represent different risks of eutrophication of the reservoir. This methodology was similar to that proposed by Chang et al. (2015).

$$\textit{Risk for the mesotrophic level} = 1 - CFD(0.027mg/L) \tag{5}$$

$$\textit{Risk for the eutrophic level} = 1 - CFD(0.053mg/L) \tag{6}$$

$$\textit{Risk for the hypereutrophic level} = 1 - CFD(0.211mg/L) \tag{7}$$

RESULTS AND DISCUSSION

Fig. 2 shows the calibration and validation of the SMAP model. The calibration showed the following statistical performances: NS = 0.72, R^2 = 0.72 and r = 0.96. For validation, the statistical performances were: NS = 0.74, R^2 = 0.75 and r = 0.86. According to the classification proposed by Moriasi et al. (2007), NS values between 0.65 and 0.75 are considered as "good". In addition, R^2 values greater than 0.5 are considered as "acceptable" (Santhi et al. 2001, Liew et al. 2003). For the metric r, Me et al. (2018)

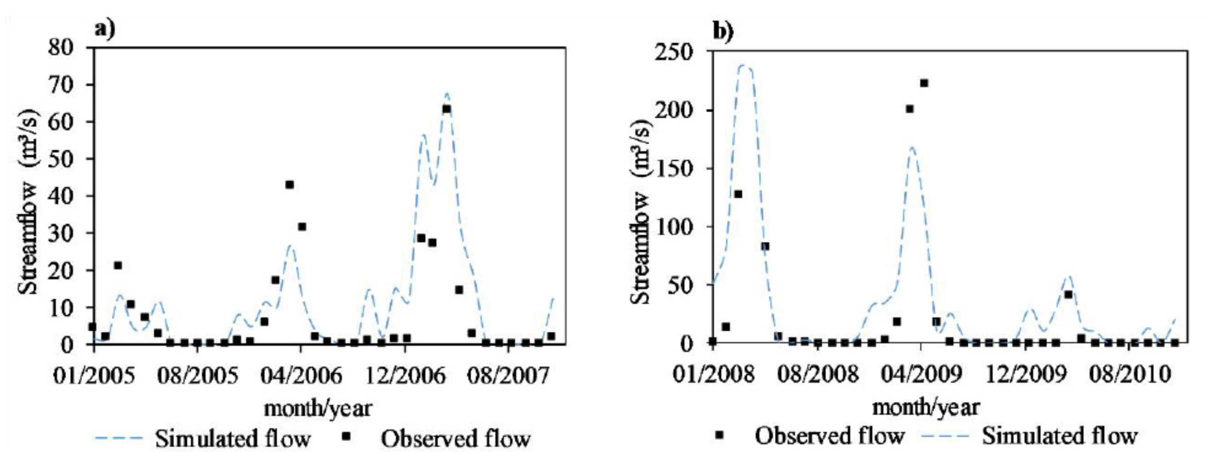

Figure 2. Calibration (2005-2007) **(a)** and validation (2008-2010) **(b)** of the SMAP model for the Orós reservoir.

considered values greater than 0.80 as “high”. Thus, these calibration and validation results obtained in the present study are considered adequate.

It is important to highlight that a model performance is crucial to carry out future projections of the influent TP concentration [Eq. (4)] when using affluent Concentration-Streamflow models (Bieroza et al. 2018, Rocha & Neto 2020).

The Table I shows the relative changes of the streamflow and of the percentage of maximum storage volume (referred herein as percent volume) in relation to 29.84 m^3/s (baseline: 1973-2000) and to 56% (baseline: 1986-2000), respectively. The five different GCMs exhibited wide variation in the relative change for both the streamflow and the percent volume. Table I also shows that the SSP5-8.5 has a greater effect on reducing streamflow compared to SSP2-4.5, with the percentage volume reproducing a similar trend.

Table I. Relative change in streamflow/percent volume using five different GCMs with two SSPs-RCPs and three future periods.

	2015-2044		2015-2044		2015-2044	
	% change		% change		% change	
GCMs	SSP2-4.5	SSP5-8.5	SSP2-4.5	SSP5-8.5	SSP2-4.5	SSP5-8.5
IPSL-CM6A-LR	633.3/76.0	39.3/75.7	602.0/75.8	677.5/74.0	599.1/74.1	757.7/74.5
BCC-CSM2-MR	37.3/54.2	23.7/42.5	33.0/55.0	-10.5/30.6	17.9/52.7	-61.3/-83.4
CanESM5	-6.9/-18.0	10.4/25.8	-3.1/-29.0	-49.0/-68.1	-10.1/3.3	-55.7/-65.9
MIROC6	41.9/41.0	43.5/10.8	56.8/59.4	-22.8/-15.4	78.6/52.9	-50.8/-63.94
MRI-ESM2-0	28.5/38.0	10.4/5.3	146.5/65.6	149.7/42.7	173.7/72.3	214.2/54.4

The divergences in the projections of the percent volume indicated the uncertainty propagation along the CGMs, SMAP and reservoir water balance. Similar results were found for the affluent flow in other studies for the Jaguaribe River basin (Fernades et al. 2017, Gondim et al. 2018). For example, (Estácio 2020) predicted relative changes varying from -50% to 300%, for the same reservoir of this study during the 2025-2055 period. Studies in other NEB regions have also presented divergences in the future projections of the streamflow (Tiezzi et al. 2019, Silva et al. 2021). Silveira et al. (2016), for example, identified variations from -70% to 40% in the streamflow of the Brazilian hydropower sector by the end of the 21st century.

Note that here is no study available on the impacts of climate change on the stored volume in the Upper Jaguaribe sub-basin. However, some studies around the world can be taken for comparison purposes. Molina-Navarro et al. (2014) and Bucak et al. (2018) also observed divergences in the projections of the future water level in Mediterranean reservoirs, but the variations observed in the present study were much more pronounced. The drop in volume was mainly a response to the diminished streamflow, which is in agreement with the findings by Molina-Navarro et al. (2014).

Fig. 3 shows the projections of representative TP concentrations in the Orós reservoir for the three future periods under SSP2-4.5 and SSP5-8.5, based on the Eq. (2). For SSP2-4.5, only 20% of the projections indicated eutrophication of the reservoir, all concentrated in a single climate model. On the other hand, SSP5-8.5 exhibited about 67% of future projections indicating eutrophication, with the last period experiencing severe degradation of water quality for most GCMs. For this SSP-RCP, at least one GCM exhibited half the time in the eutrophic or hypereutrophic states in the three periods, with a strong decline in water quality at the end of the 21st century.

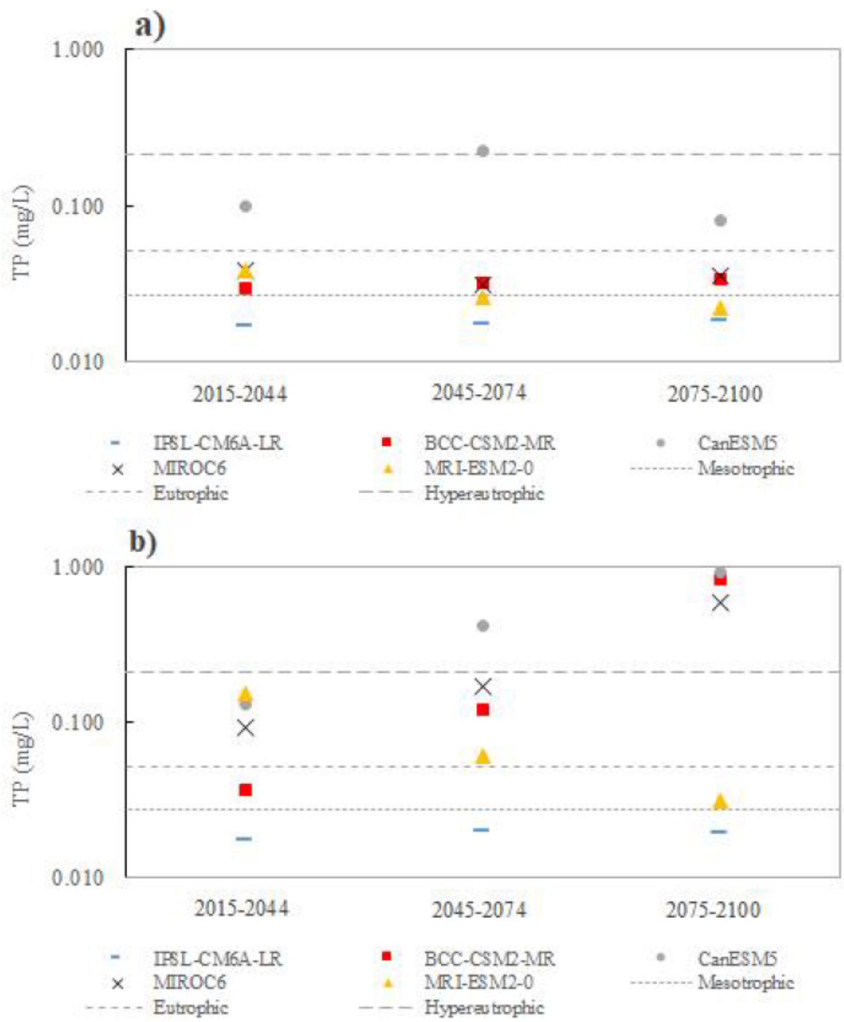

Figure 3. Projections of the representative values of TP concentration in Orós reservoir using five different GCMs with two SSPs-RCPs and three future periods. a) scenario SSP2-4.5; b) scenario SSP5-8.5.

These results differ from the findings by Zhang et al. (2019), who projected a further decline in water quality under SSP2-4.5, indicating that the impacts of climate change depend on the region studied (Coops et al. 2003). The probable physical explanation was the decrease in the streamflow, which reduced the dilution capacity of the influent TP concentration, and the increase in the hydraulic residence time (Nazari-Sharabian et al. 2018). This trend was identified in this work under SSP5-8.5, which is consistent with the observations made in the NEB's reservoirs (Zwolsman & Bokhoven 2007, Araújo et al. 2021, Raulino et al. 2021) and in other studies on the impacts of climate change on water quality of reservoirs (Molina-Navarro et al. 2014). In addition, under SSP5-8.5, the largest reductions in the volume were projected, which implies an increase in the internal TP concentration (Mesquita et al. 2020, Wiegand et al. 2021). These factors can promote rapid algal growth (Nazari-Sharabian et al. 2018).

It is important to note that several other studies have identified a greater tendency for water quality degradation in the reservoirs investigated also under SSP5-8.5 (Couture et al. 2018, Chang et al. 2015, Bucak et al. 2018, Shalby et al. 2020). These results, together with those found in this work, indicate that the most pessimistic emission scenario (SSP5-8.5) has the capacity to interfere more significantly in the streamflow and percentage volume and, consequently, in the water quality of reservoirs and lakes (Me et al. 2018, Nazari-Sharabian et al. 2019a, Messina et al. 2020).

The linear regression analysis revealed a strong negative correlation between the average TP concentration in the reservoir and its percent volume (R^2 = 0.96). Junior et al. (2018) found an equivalent result when investigating reservoirs in two semi-arid sub-basins in the State of Rio Grande do Norte, Brazil. It is important to highlight that the decrease in the streamflow can also contribute to the degradation of water quality, since low flows reduce the self-purification potential of the river that transports pollutants from the basin to the reservoir (Araújo et al. 2021, Lira et al. 2020, Mesquita et al. 2020).

Although future TP concentrations can offer an overview of the climate change impacts on water quality of the reservoir (see Fig. 4), the information generated may be inadequate or incomplete for water management decision-making (Glavan et al. 2015, Couture et al. 2018, Messina et al. 2020). These uncertainties, therefore, hamper the sustainable management of reservoir water quality, especially when there are divergences in the signal in the future projections of the water quality state variables.

Fig. 4 shows the probability risks of exceeding the trophic levels of the Orós reservoir for the three future periods under the SSP2-4.5 and SSP5-8.5. The results showed that the intensification of the trophic condition of the reservoir is more likely to occur in the SSP5-8.5. Nevertheless, the three periods showed a non-null risk of eutrophication under the two SSPs-RCPs. A visual inspection showed a clear difference in the risk curve for the last period of SSP5-8.5 compared to the curves of the other periods, indicating that the Orós reservoir may be strongly susceptible to eutrophication at the end of the 21st century. The fact that the hypereutrophic state in the baseline was not observed is a relevant information, since all the aggregated scenarios (SSPs-RCPs plus future periods) indicated a probability of exceeding the hypereutrophic level greater than zero, with the highest risk being projected for the last period under SSP5-8.5 (38.5%). In this sense, climate change can intensify the trophic condition of the Orós reservoir and favor eutrophication, as stated by Chang et al. (2015) for reservoir in a humid-subtropical climatic region and Messina et al. (2020) for a temperate lake. Therefore, climate change and its potential effects on eutrophication put more pressure on water resources (Nazari-Sharabian et al. 2018), especially in NEB, which is already marked by frequent droughts and water deficits (Campos 2015).

Fig. 5 shows the seasonality of TP concentration in the Orós reservoir. All scenarios aggregated in the dry period (June to January) showed an intensification of the trophic condition relative to the wet period (February to May). Even the most optimistic GCMs projected higher medians of TP concentrations during the dry period. Overall, the higher TP-values in the dry period are attributed to the combined effects of higher inlet concentrations during low flows, lower settling loss rates due to higher hydraulic residence times, and higher internal TP concentrations due to the reduced volumes [see Eqs. (2), (3) and (4)]. The same seasonal trends of TP concentration were also observed in the field studies conducted by Araújo et al. (2021) in a small reservoir located in the State of Ceará. Although not included in the present TP modelling for the sake of simplicity and lack of field data, the internal

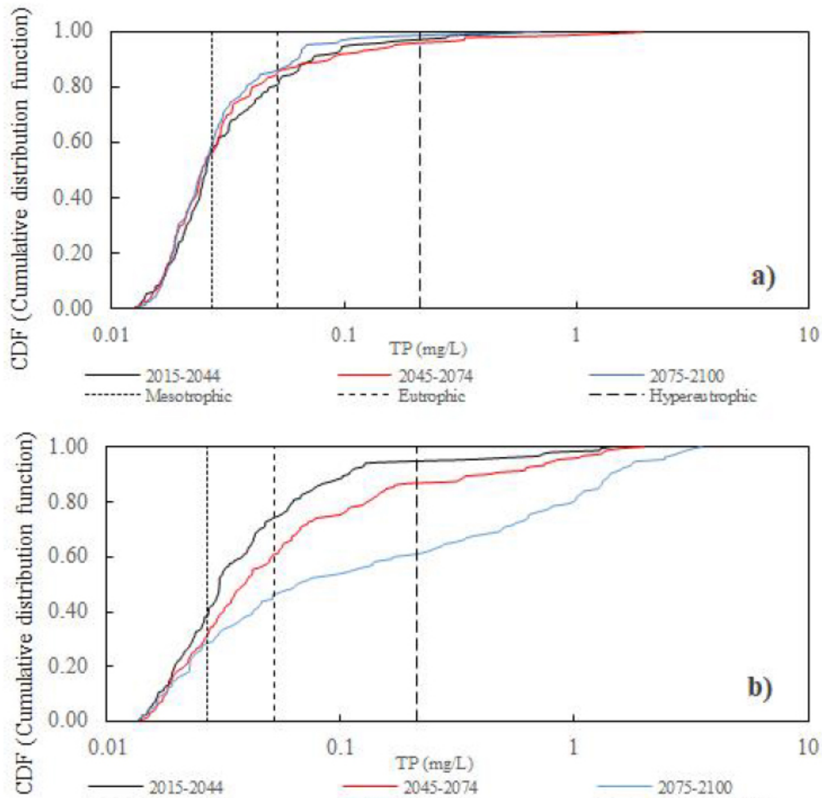

Figure 4. Probabilistic risks of trophic levels using the outputs of five different GCMs under **a)** SSP2-4.5 and **b)** SSP5-8.5, and three future periods.

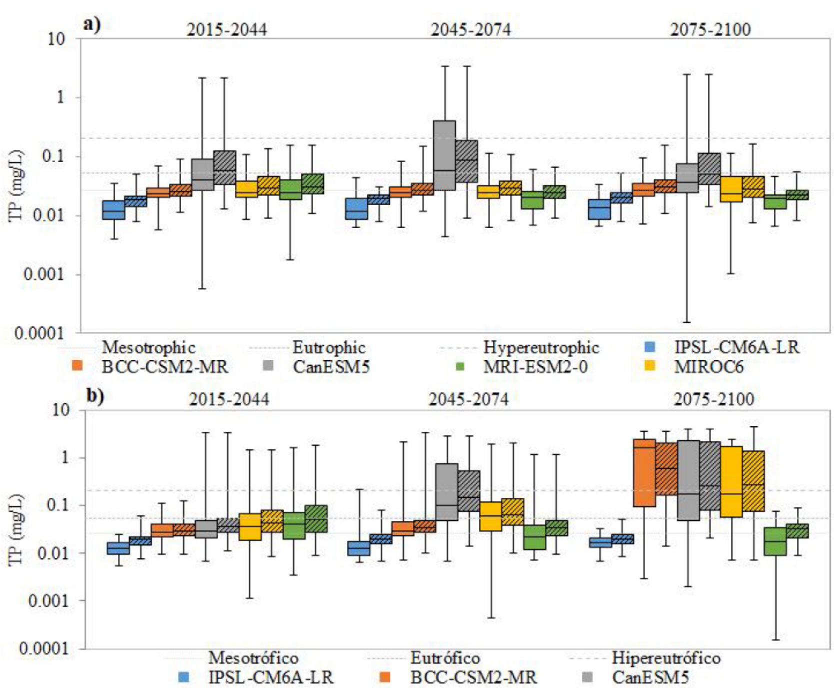

Figure 5. Seasonality of Total Phosphorus (TP) concentration in Orós reservoir using five different GCMs under **a)** SSP2-4.5 and **b)** SSP5-8.5 scenarios and three future periods. The rectangles without diagonal lines represent the rainy season, while the rectangles with diagonal lines, the dry season.

phosphorus load may also contribute to increased TP concentration during the dry season, as already observed by Lira et al. (2020) and Moura et al. (2020) in reservoirs also located in the State of Ceará.

Table II. Probability of exceeding Phosphorus (TP) levels in the Orós Reservoir.

		2015-2044		2015-2044		2015-2044	
		Risk (%)		Risk (%)		Risk (%)	
TP (mg/L)	Period	SSP2-4.5	SSP5-8.5	SSP2-4.5	SSP5-8.5	SSP2-4.5	SSP5-8.5
≥ 0.027	Feb-May	40.5	47.0	35.5	53.8	34.8	58.8
	June-Jan	52.1	50.8	48.9	70.2	49.6	74.2
≥ 0.052	Feb-May	15.8	23.5	13.0	33.8	12.7	47.3
	June-Jan	22.0	27.3	17.2	39.1	15.8	55.6
≥ 0.211	Feb-May	3.0	5.0	6.0	12.3	2.5	33.3
	June-Jan	3.0	5.0	6.0	13.1	2.6	36.6

The average TP concentrations in the rainy and dry periods organized as CDFs confirmed that the water quality of the Orós reservoir is more vulnerable in the dry period of the year (Table II). The greatest vulnerability in the dry period is one of the properties highlighted in the synthesis of water bodies in the semiarid region of Brazil carried out by Barbosa et al. (2012). These findings are in the same direction as the results found in the study by Zhang et al. (2019). In addition, the seasonality of the streamflows and the intermittency of the rivers have been associated with a degradation of water quality in the Brazilian semiarid (Lima et al. 2018, Araújo et al. 2021, Lira et al. 2020, Raulino et al. 2021). This brings an alert for part of the projections, especially considering the low coverage of basic sanitation (33%) in the Upper Jaguaribe sub-basin (COGERH 2011).

Simulations of realistic reductions ranging from 10-30% in the influent TP concentration and reservoir withdrawal were performed in order to assess the effect of these variables on the trophic state of the reservoir (Table III).

Under SSP2-4.5, the reduction in the influent TP concentration individually was not able to mitigate the eutrophication for the CanESM5 model. However, the most pronounced reductions (-30%) in the two investigated variables managed to reduce the degradation of water quality in the three periods, reaching the mesotrophic level for all of them. Under SSP5-8.5, only simultaneous reductions in the influent TP concentration and reservoir withdrawal were able to reduce the trophic status from eutrophic to mesotrophic in the first period. The application simultaneous measures to improve water quality in reservoirs was also suggested by Yazdi & Moridi (2017), Azadi et al. (2019) and Nazari-Sharabian et al. (2019b). In the last period, even with the proposed reductions, most GCMs projected eutrophication. Bucak et al. (2018) found similar results when investigating Beysehir Lake in a Mediterranean basin in Turkey, including the inefficiency of strategies to mitigate eutrophication in some cases. Zhang et al. (2019) also observed results in the same direction, indicating that, even with significant reductions in the influent TP concentration and major withdrawal restrictions, the risk of eutrophication was still relatively high. On the other hand, Molina-Navarro et al. (2014) verified the potential of land use management to reduce the trophic state of water bodies, with

Table III. Simulations of reductions in the influent Phosphorus Total (TP) concentration and reservoir withdrawal. Note that realistic reductions of 10-30% were considered.

SSP2-4.5								
			2015-2044		2015-2044		2015-2044	
GCMs	c_a	Q_{90}	TP (mg/L)	%change	TP (mg/L)	%change	TP (mg/L)	%change
IPSL-CM6A-LR	↓ 10 – 30	-	(0.015)-(0.012)	(-71.9)-(-78.1)	(0.016)-(0.012)	(-70.7)-(-77.2)	(0.017)-(0.013)	(-69.2)-(-76.0)
	↓ 10 – 30	↓ 10 – 30	(0.015)-(0.012)	(-71.9)-(-78.1)	(0.016)-(0.012)	(-70.7)-(-77.2)	(0.017)-(0.013)	(-69.2)-(-76.0)
BCC-CSM2-MR	↓ 10 – 30	-	(0.027)-(0.021)	(-50.7)-(-61.5)	(0.029)-(0.022)	(-47.3)-(-59.0)	(0.031)-(0.024)	(-43.6)-(56.1)
	↓ 10 – 30	↓ 10 – 30	(0.026)-(0.020)	(-51.2)-(-63.3)	(0.028)-(0.021)	(-48.3)-(-61.6)	(0.030)-(0.023)	(-44.6)-(-58.5)
CanESM5	↓ 10 – 30	-	(0.128)-(0.100)	(136.3)-(83.9)	(0.285)-(0.222)	(426.3)-(309.3)	(0.105)-(0.081)	(93.0)-(50.1)
	↓ 10 – 30	↓ 10 – 30	(0.085)-(0.042)	(56.9)-(-23.1)	(0.199)-(0.048)	(267.2)-(-11.7)	(0.063)-(0.039)	(18.0)-(-28.5)
MIROC6	↓ 10 – 30	-	(0.034)-(0.027)	(-36.6)-(-50.6)	(0.028)-(0.022)	(-48.3)-(-59.8)	(0.032)-(0.025)	(-41.4)-(-54.4)
	↓ 10 – 30	↓ 10 – 30	(0.033)-(0.025)	(-38.8)-(-53.8)	(0.028)-(0.022)	(-48.5)-(-60.1)	(0.031)-(0.024)	(-41.9)-(-55.3)
MRI-ESM2-0	↓ 10 – 30	-	(0.035)-(0.027)	(-36.0)-(-50.1)	(0.023)-(0.018)	(-56.9)-(-66.5)	(0.020)-(0.015)	(-63.4)-(-71.5)
	↓ 10 – 30	↓ 10 – 30	(0.034)-(0.025)	(-37.9)-(-53.4)	(0.023)-(0.018)	(-56.9)-(-66.4)	(0.020)-(0.016)	(-63.4)-(-71.2)
SSP2-8.5								
IPSL-CM6A-LR	↓ 10 – 30	-	(0.016)-(0.012)	(-71.4)-(-77.6)	(0.018)-(0.014)	(-67.3)-(74.5)	(0.017)-(0.013)	(-68.0)-(-75.1)
	↓ 10 – 30	↓ 10 – 30	(0.016)-(0.012)	(-71.4)-(-77.6)	(0.018)-(0.014)	(-67.3)-(74.5)	(0.017)-(0.013)	(-68.0)-(-75.1)
BCC-CSM2-MR	↓ 10 – 30	-	(0.032)-(0.025)	(-40.1)-(-53.3)	(0.107)-(0.083)	(97.9)-(53.9)	(0.755)-(0.587)	(1292.9)-(983.4)
	↓ 10 – 30	↓ 10 – 30	(0.031)-(0.024)	(-42.3)-(-56.4)	(0.090)-(0.040)	(65.2)-(-25.4)	(0.677)-(0.343)	(1148.7)-(533.4)
CanESM5	↓ 10 – 30	-	(0.117)-(0.091)	(115.9)-(68.2)	(0.373)-(0.290)	(588.6)-(435.6)	(0.824)-(0.641)	(1419.4)-(1081.8)
	↓ 10 – 30	↓ 10 – 30	(0.098)-(0.037)	(79.9)-(-32.2)	(0.279)-(0.113)	(415.2)-(107.7)	(0.719)-(0.421)	(1225.9)-(677.2)
MIROC6	↓ 10 – 30	-	(0.084)-(0.065)	(54.0)-(19.9)	(0.151)-(0.117)	(177.6)-(115.9)	(0.534)-(0.416)	(885.7)-(666.6)
	↓ 10 – 30	↓ 10 – 30	(0.051)-(0.042)	(-6.0)-(-22.3)	(0.104)-(0.086)	(91.4)-(59.4)	(0.492)-(0.391)	(808.1)-(621.6)
MRI-ESM2-0	↓ 10 – 30	-	(0.136)-(0.106)	(150.8)-(95.2)	(0.054)-(0.042)	(-0.4)-(-22.5)	(0.028)-(0.022)	(-48.0)-(-59.5)
	↓ 10 – 30	↓ 10 – 30	(0.081)-(0.039)	(50.0)-(-54.4)	(0.049)-(0.025)	(-9.1)-(-54.4)	(0.028)-(0.021)	(-48.4)-(-60.4)

all the scenarios studied indicating oligotrophic or mesotrophic states. However, in their case, the baseline configuration itself, in relation to land use and nutrient loadings, and the relatively low variability of streamflow and stored volume, potentially contributed to more optimistic projections of TP concentration.

These results revealed that, even with the proposed reductions, climate change will potentially intensify the eutrophication process in the reservoir, especially at the end of the 21st century (Couture et al. 2014). Similar impacts of climate change on water quality deterioration were also reported by Molina-Navarro et al. (2014), Bucak et al. (2018) and Nazari-Sharabian et al. (2019a). However, the impacts were much more pronounced in the present study, as a response of the higher variability of streamflow and stored volume. This suggests that tropical semiarid reservoirs could be more vulnerable to eutrophication in scenarios of climate change than in other regions around the world. However, it was possible to identify a reduction in the risk of eutrophication due to the proposed measures (Table IV). In this sense, Best Management Practices (BMPs) can be used to adequately control the TP load in the reservoir (Babaei et al. 2019).

Table IV. Effects of reductions in the influent Phosphorus Total (TP) concentration and reservoir withdrawal on the risk of eutrophication for two emission scenarios and three future periods.

			2015-2044		2015-2044		2015-2044	
			Risk (%)		Risk (%)		Risk (%)	
c_a	Q_{90}	TP (mg/L)	SSP2-4.5	SSP5-8.5	SSP2-4.5	SSP5-8.5	SSP2-4.5	SSP5-8.5
-	-	≥ 0.052	22.7	25.3	16.7	38.7	16.2	53.8
-	-	≥ 0.211	4.0	4.7	6.0	13.3	2.3	39.2
↓ 10 – 30	-	≥ 0.052	(18.0)-(10.0)	(23.3)-(16.0)	(15.3)-(13.3)	(34.7)-(26.7)	(13.8)-(6.9)	(51.5)-(47.7)
↓ 10 – 30	-	≥ 0.211	(3.3)-(2.7)	(4.7)-(4.7)	(4.7)-(4.0)	(12.7)-(12.7)	(1.5)-(0.8)	(37.7)-(23.8)4
↓ 10 – 30	↓ 10 – 30	≥ 0.052	(16.0)-(6.0)	(22.0)-(10.0)	(14.7)-(6.0)	(32.7)-(18.7)	(12.3)-(3.8)	(50.8)-(45.5)
↓ 10 – 30	↓ 10 – 30	≥ 0.211	(1.3)-(0.0)	(10.0)-(0.0)	(2.7)-(0.0)	(8.7)-(1.3)	(0.8)-(0.0)	(33.8)-(19.2)

CONCLUSIONS

This study evaluated the impacts of climate change on the risk of eutrophication of a large reservoir in the Brazilian semiarid region. The following conclusions can be drawn from the results:

- The streamflows and percent volumes projected from the five different GCMs showed a strong divergence both in magnitude and signal for the three future periods. The divergences were more pronounced under SSP5-8.5, with the last period indicating negative changes for most GCMs;

- The divergences in the projections were also observed in the future TP concentrations in the reservoir, suggesting the propagation of uncertainties along the steps of the integrated modeling. Under SSP2-4.5, most GCMs projected a reduction in the average TP concentration, but SSP5-8.5 pointed to a significant increase in the TP concentration for most GCMs;

- The uncertainties observed in the average TP concentration required a more convenient response to properly assist in the decision making. The risk assessment revealed a chance of eutrophication for the three periods and the two SSPs-RCPs, with a higher probability of a decline in water quality at the end of the 21st century for SSP5-8.5;

- The seasonality analysis showed that the dry period is more susceptible to eutrophication than the rainy period;

- The simulations revealed that the reduction in the influent TP concentration alone was insufficient to reduce the high TP concentrations in the reservoir projected by some climate models. On the other hand, simultaneous reductions in both influent TP concentration and reservoir withdrawal are capable of significantly reducing the trophic state of the reservoir in most pessimistic scenarios;

- The impact of climate change on reservoir water quality was much more pronounced in the present study than reported in the literature for other regions of the globe;

- Finally, we concluded that the eutrophication risk assessment is important to provide relevant information for water resources management, specially in water-scarce regions such as the Brazilian semiarid.

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