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Assessment of climate change impacts on hydrology and water quality of large semi-arid reservoirs in Brazil

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ABSTRACT

This paper investigates climate change impacts on the hydrology and water quality of Brazilian semi-arid reservoirs. An integrated approach coupling climate, hydrological and water quality models was proposed. Five general circulation models (GCMs) and two future scenarios (SSP2-4.5 and SSP5-8.5) were used for the projections. The simulations showed that uncertainty in climate forecast significantly impacted hydrological and water quality outputs. Some scenarios revealed a strong decrease in streamflow and storage volume. On the other hand, 40% of multi-GCM projections indicated reservoir eutrophication. The impacts on hydrology and water quality under SSP5-8.5 were more significant than those under SSP2-4.5. The results also indicated that drought events may be prolonged under climate change, principally at the end of the 21st century for SSP5-8.5, and may significantly increase the total phosphorus concentration. This suggests that tropical semi-arid reservoirs could be more vulnerable to eutrophication in scenarios of climate change than those in other regions.

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climate change; hydrology; eutrophication; water quality; prolonged droughts; semi-arid

1 Introduction

Water shortage and water pollution have impacted negatively on the water resources of Northeast Brazil (NEB), causing major harm to the population and regional development. For instance, in the Brazilian state of Ceará, the current storage percentage of the 155 reservoirs monitored by the Water Resources Management Company of Ceará (COGERH) is only about 30%, and 92 of the 127 qualitatively monitored reservoirs are already eutrophic (COGERH 2020). On the other hand, the Middle Jaguaribe sub-basin, the focus of the present study, only treats 33% of its sewage (COGERH 2011), a value close to that of NEB (36%) (National Sanitation Information System (SNIS) 2019).

The nutrient inputs from untreated sewage, agricultural practices and livestock farming are mostly responsible for the eutrophication of the water bodies (du Plessis *et al.* 2015, Klippel *et al.* 2020). Eutrophication may favour cyanobacteria blooms, which could have a negative effect on the aquatic ecosystem, water treatment and the population's health (Carvalho *et al.* 2013, Pacheco and Lima Neto 2017, Lima *et al.* 2018).

Droughts that periodically affect NEB and high evaporation rates (Campos 2015) are responsible for gradual declines in the storage volume of the Brazilian semi-arid reservoirs (Braga *et al.* 2015). Moreover, due to the intermittent river regime in NEB, in the dry seasons, essentially untreated sewage is transported to the reservoirs (Araújo *et al.* 2019, Fraga *et al.* 2020, Mesquita *et al.* 2020). In this respect, the water quality in lakes and reservoirs in semi-arid areas can be particularly sensitive to the effects of the hydroclimatic variability, since the water quality is closely linked to the streamflow and storage

volume of such water bodies (Chaves *et al.* 2013, Santos *et al.* 2014, Paula Filho *et al.* 2019, Wiegand *et al.* 2021).

In this context, climate change can affect the water quality of NEB reservoirs more drastically (Rocha Junior *et al.* 2018, Lisboa *et al.* 2020). However, all studies of the impacts on climate change in the NEB and, more specifically, in the Jaguaribe River basin, have concentrated only on quantitative aspects of the water resources (e.g. Gondim *et al.* 2012, 2018, Fernandes *et al.* 2017, Silveira *et al.* 2017, Tiezzi *et al.* 2019). This scarcity of studies on the qualitative nature of water resources in the region is a concern since several studies around the world have shown that climate change can have adverse effects on the water quality in water bodies and can intensify many forms of water pollution (e.g. Couture *et al.* 2014, 2018, Bucak 2018, Me *et al.* 2018, Zhang *et al.* 2019). Therefore, to ensure the supply of good-quality water for future generations, it is important to assess the impacts of climate change on water quality. This context is one reason why this study is necessary and able to offer valuable contributions to the NEB.

Phosphorus is considered the limiting nutrient of eutrophication of inland water bodies (Chapra 2008), and the control of cyanobacterial blooms and other symptoms of eutrophication depends primarily on the reduction of phosphorus inputs (Schindler *et al.* 2016). Hence, several studies have considered the total phosphorus (TP) concentration as a variable representing the water quality to investigate the phenomenon of eutrophication in lakes and reservoirs around the world (Lima *et al.* 2018, Nazari-Sharabian *et al.* 2019, Rocha *et al.* 2019, Zhang *et al.* 2019, Moura *et al.* 2020). In addition, for reservoirs in the tropical semi-arid region, eutrophication is

strongly related to gradual reductions in the stored volume (Rocha Junior *et al.* 2018), high temperatures (Toné and Lima Neto 2020), daily stratification (Lima Neto 2019) and seasonality of the streamflow (Araújo *et al.* 2019), characteristics that can be used to describe the water quality of reservoirs in the region using the TP concentration. In this sense, the complete mixing model proposed by Vollenweider (Organisation for Economic Co-operation and Development (OECD) 1968) and its derivations have been successfully applied to estimate the TP concentration of lakes and reservoirs (Nielsen *et al.* 2013, Molina-Navarro *et al.* 2014, Trolle *et al.* 2015, Lira *et al.* 2020, Mesquita *et al.* 2020).

The prime purpose of this study was to assess the impact of climate change on water quality in the Castanhão reservoir, which is located in the semi-arid region of the Brazilian state of Ceará, and is considered the largest multi-use reservoir of Latin America. The impacts on the streamflow and water level in the reservoir were also investigated. The study included the integration of five different general circulation models (GCMs), a hydrological model and a water quality model to forecast the future trophic status of the reservoir. The effects of two emission scenarios were assessed on the trophic status in three future periods.

2 Materials and methods

2.1 Study area

The Brazilian state of Ceará is located in NEB (Fig. 1), and more than 90% of its territory is located in the country's semi-arid region (Pontes Filho *et al.* 2020). Ceará, including the entire Northeastern region, is marked by extreme climate events, including periodic droughts and sporadic flooding.

The inter-annual variability is high due to the El Niño-Southern Oscillation (ENSO; Luiz Silva *et al.* 2021). The main active meteorological system is the Intertropical Convergence Zone (ITCZ), responsible for the state's rainy season, between February and May (Gondim *et al.* 2018). There are two other operating systems, albeit these are less relevant: cold fronts and cyclonic eddies, responsible for the pre-rainy season (December–January); and the easterly waves, responsible for the post-rainy season (June–July) (Cavalcanti *et al.* 2011, Gomes *et al.* 2015). Generally speaking, however, the year has two very different seasons; one wet, from February to May, with around 75% of the annual rain falling in this season; and the other dry, during the remaining months (Campos *et al.* 2014). As a result, a strategy has been adopted to build reservoirs distributed over the state territory to store water in the wet season and rainy years in order to meet water requirements in the dry season and drought years (Campos 2015).

Castanhão reservoir (6700 hm³), located in the Ceará municipality of Alto Santo and the largest multi-use reservoir of Latin America, lies within the Jaguaribe River basin, well known for its vast expanse covering practically half of the Ceará territory (72 645 km², 48% of the total area of the state). The Jaguaribe River, which is the main water supply of the basin, stretches for 610 km from its source to where it drains into the Atlantic Ocean. The Jaguaribe River basin is divided into five sub-basins: Upper, Middle and Lower Jaguaribe, Salgado and Banabuiú. Castanhão reservoir is part of the Middle Jaguaribe sub-basin. This sub-basin, together with its tributaries, is located in the eastern part of Ceará State and covers an area of around 10 355 km² (13% of Ceará territory), with the River Jaguaribe being the largest river in this sub-basin (Fig. 1). The climate of this sub-basin has semi-

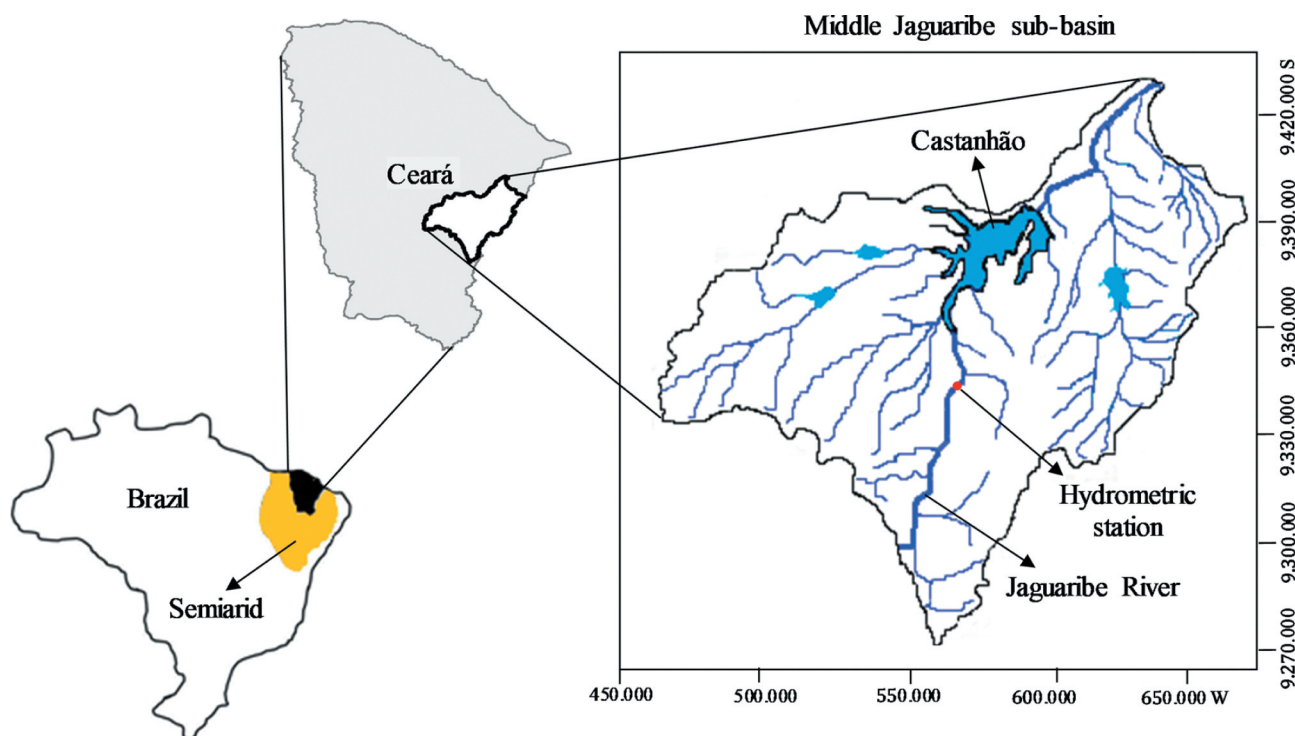


Figure 1. Map of Castanhão reservoir in the sub-basin of the Middle Jaguaribe River, State of Ceará, Brazil.

arid characteristics, with an annual average temperature of 28°C and annual average rainfall of approximately 700 mm. The association of the high concentration of the rainfall system in 4 months of the year (75% of total rainfall) with the crystalline soil covering more than 80% of the basin results in the intermittence of the Jaguaribe River (Campos *et al.* 2014).

Located upstream of Castanhão, in the Upper Jaguaribe River Basin, the Orós is the second largest multi-use reservoir (1940 hm³) in the state of Ceará (see Lima Neto *et al.* 2011). This reservoir was also included in the analysis of the present study for purposes of comparison with the Castanhão reservoir.

2.2 Modelling

In this study, a combined approach of climate, hydrological and water quality models was adopted to characterize the Castanhão reservoir water quality under climate change scenarios. After calibrating and validating the SMAP hydrological model, future streamflow of the reservoir was projected under SSP2-4.5 and SSP5-8.5, using climate projections of CMIP 5 models, viz. BCC-CM6A-LR, CanESM5, IPSL-CM6A-302 LR, MIROC6 and MRI-ESM2-0. The nutrient load was simulated, using a correlation between the reservoir's inflow and the TP concentration at the reservoir's inlet. The land use of the sub-basin was considered unaltered in the modelling process. The future volume of the reservoir was calculated from its water balance. These two variables (streamflow and storage volume) were the main input data for the empirical Vollenweider model (OECD 1968), applied in this study to determine the reservoir's water quality. The average TP concentration within the reservoir was used as a water quality status for the three future periods (2015–2044, 2045–2074 and 2075–2100). The water quality data-logging period, 2008–2014, was used as the baseline. The transient version of the model was used, also considering the high water-level variability of the reservoir. According to the future TP concentrations, the reservoir's trophic status was classified for each of the three future periods investigated to assess the possible eutrophication of the reservoir in response to climate change.

2.3 SMAP hydrological model

2.3.1 Model structure

The hydrological model to be used in this research is the monthly version of SMAP, initially developed by Lopes *et al.* (1982) and recently described by Fernández Bou *et al.* (2015). The SMAP has been successfully applied to a number of Brazilian basins (Block *et al.* 2009, Kwon *et al.* 2012, Fernández Bou *et al.* 2015, Silveira *et al.* 2017, Da Silva *et al.* 2018, Gondim *et al.* 2018, Tiezzi *et al.* 2019, De Paiva *et al.* 2020, Silva *et al.* 2021). This is a rainfall hydrological simulation model, classified also as deterministic, conceptual and with lumped structure. The monthly version of SMAP contains two linear reservoirs (soil reservoir, R_{soil} ; and groundwater, R_{gw}) and four parameters: soil storage capacity (SAT) in mm; surface flow parameter (Kes), dimensionless; recharge coefficient (Crec), dimensionless, and base flow recession coefficient (K) in

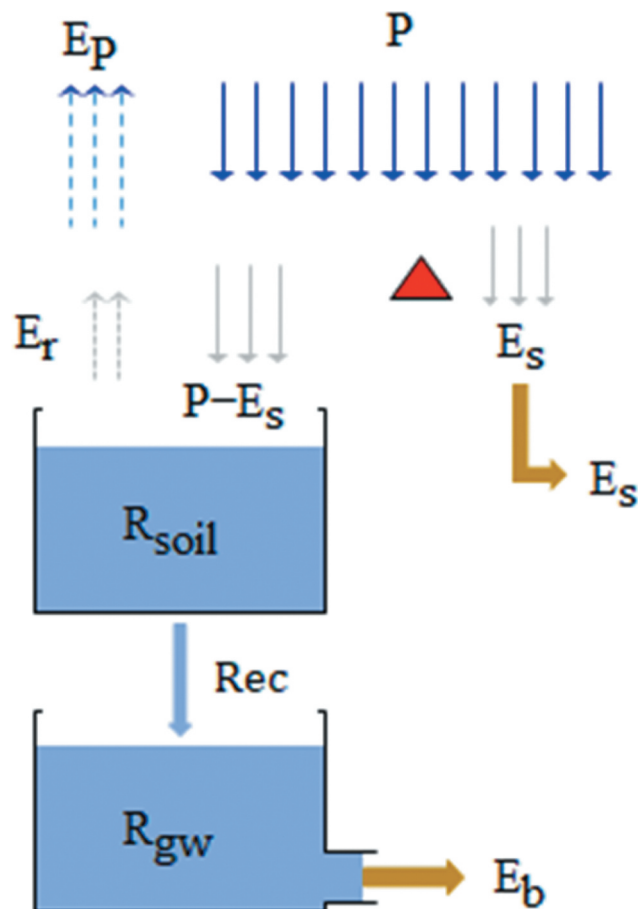


Figure 2. Conceptual illustration of the SMAP hydrological model used in this study (Kwon *et al.* 2012).

a month. The separation between rainfall and surface runoff is based on the Soil Conservation Service (SCS) equation. Figure 2 represents the model's structure with its two linear reservoirs.

Further details on the operation of the SMAP hydrological model can be found in Lopes *et al.* (1982), Kwon *et al.* (2012) and Silva *et al.* (2021).

2.3.2 Calibration and validation

The SMAP calibration process consisted of optimizing the SAT, Kes, Crec and K parameters with the Nash-Sutcliffe (NS) efficiency coefficient as an objective function. In addition, another two metrics were calculated to supplement the statistical evaluation of the SMAP, namely Pearson's correlation coefficient (Correl) and the determination coefficient (R^2) (Moriassi *et al.* 2007).

The periods 1981–1995 and 1996–2010 were used for calibration and validation, respectively. Streamflow data were collected from the Brazilian National Water Agency (ANA) website (<http://www.snirh.gov.br/>). The precipitation data from the stations with influence on the Middle Jaguaribe sub-basin were obtained from the Ceará State Foundation for Meteorology and Water Resources (FUNCEME) (<http://www.funceme.br/>). The average monthly rainfall in the sub-basin was calculated based on the Thiessen method, while the Climate Normal of the potential evapotranspiration was

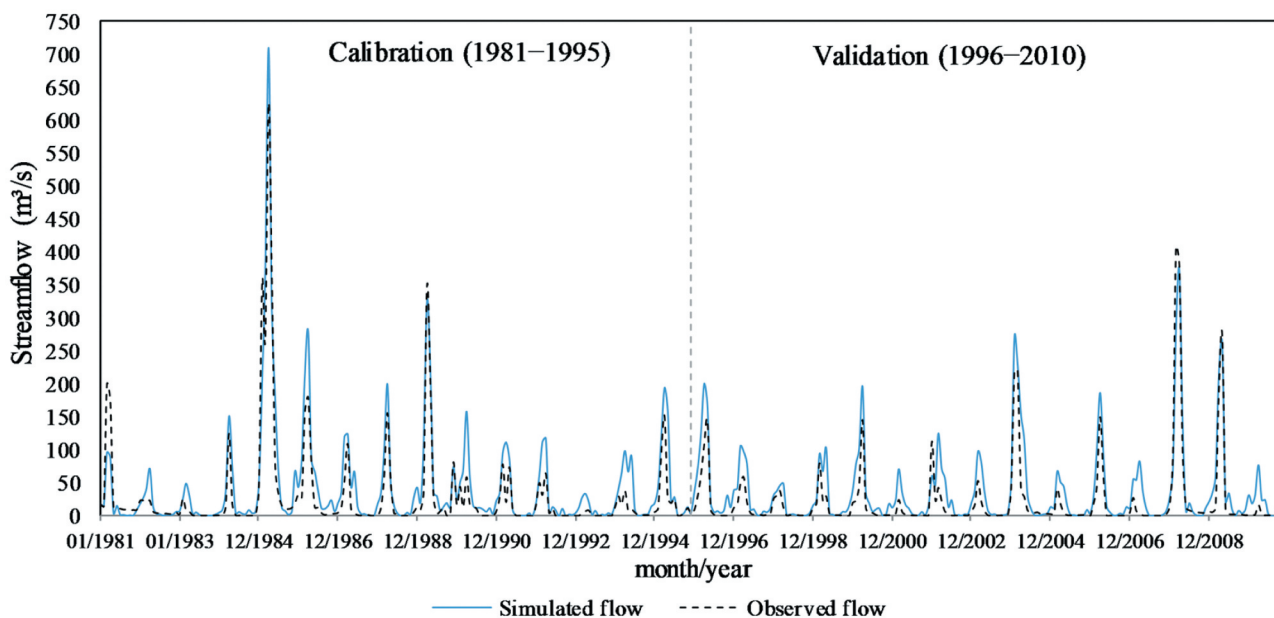


Figure 3. Calibration and validation of the SMAP model for Castanhão reservoir.

provided by the National Institute of Meteorology (INMET) (<http://www.inmet.gov.br/>).

Figure 3 shows the results of the calibration and validation of the SMAP for Castanhão reservoir. The SMAP satisfactorily reproduced the streamflow pattern, presenting a superior performance in the model's validation period. The calibration provided the following statistics: Correl = 0.92; $R^2 = 0.85$ and NS = 0.80. In turn, for validation, the statistics were: Correl = 0.93; $R^2 = 0.86$ and NS = 0.77. According to the criteria set by Moriasi *et al.* (2007) for assessing the performance of models in the calibration and validation processes, an NS value between 0.50 and 0.65 is considered “satisfactory,” a value between 0.65 and 0.75 is characterized as “good,” and a value between 0.75 and 1.0 is considered “very good.” Therefore, the calibration and validation fell into the very good category. Furthermore, Zhang *et al.* (2019) consider $R^2 > 0.5$ to be a suitable value for hydrological modelling.

2.4 Scenarios of climate change

In this study, five GCMs (BCC-CM6A-LR, CanESM5, IPSL-CM6A-LR, MIROC6 and MRI-ESM2-0) of the Coupled Model Intercomparison Project 6 (CMIP6) (website: <https://esgf-node.llnl.gov/search/cmip6/>) were used. These climate models were forced by the SSP2-4.5 and SSP5-8.5 scenarios in order to obtain future rainfall and temperature values. The SSP5-8.5 was chosen because it represents the most pessimistic scenario of greenhouse gas emissions, while SSP2-4.5 was chosen because it assumes that the levels of greenhouse gas emissions will be maintained (O'Neill *et al.* 2014). The projections of the climatic variables (precipitation and temperature) were interpolated from GCMs grids to the basin area. A bias was corrected using the cumulative density function (CDF) with gamma distribution. The observed data came from the Climatic Research Unit (CRU) for the period 1971–2000 and the GCM outputs from the hindcasts for this same period. The

methodologies adopted were similar to those used by Block *et al.* (2009) and Gondim *et al.* (2018) for the statistical corrections of precipitation and temperature, respectively, and more details on the procedures can be found in those sources. Future projections of precipitation and temperature were made for three periods: 2015–2044, 2045–2074 and 2075–2100. The same bias-correction used in historical projections was used for future climatic projections. Potential evapotranspiration in future conditions was calculated from corrected temperature using the Hargreaves-Samani (HS) method (Hargreaves and Samani 1985). After this step, the climate variable projections (precipitation and potential evapotranspiration) were used to run the SMAP model for the periods 2015–2044, 2045–2074 and 2075–2100, to simulate the Castanhão future streamflow.

2.5 Water balance and water level

The future water level of the Castanhão reservoir under climate change scenarios was determined from its water balance. The reservoir's outflow was considered with its regularized streamflow. The regulated flow is defined as the streamflow to the reservoir with 90% reliability (Campos *et al.* 2016). The water loss from the reservoir's surface was considered the product of the difference between evaporation and direct precipitation and the reservoir area, relating to the net surface. The expression governing the water balance of reservoir is as follows (Campos *et al.* 2014).

$$V_{i+1} = V_i + Q_{a,i} - Q_{r,i} - EL_i A_i - S_i \quad (1)$$

where $i + 1$ (T) and i (T) refer to present and past time, respectively; V (L^3) is the water volume; Q_r ($L^3 T^{-1}$) denotes the total reservoir withdrawals; EL (LT^{-1}) is the average water loss from the reservoir; A (L^2) represents the reservoir's net surface area, and S ($L^3 T^{-1}$) is the reservoir's outflow through the spillway.

The value of the regularized streamflow (30.21 m³/s) and the depth-area-volume (DAV) curve were obtained from COGERH (<http://www.hidro.ce.gov.br/>). The monthly net evaporation vector of Castanhão reservoir was procured from a study by ANA (2017) on the Brazilian semi-arid reservoir region.

A useful ratio to assess the water level in lakes and reservoirs is the percent volume, defined as the ratio between the reservoir's storage volume and its maximum volume. This ratio is described mathematically below:

$$V_p = \left(\frac{V}{V_{\max}} \right) \times 100(\%) \quad (2)$$

where V_p is the percentage of maximum storage volume of the reservoir (here termed percent volume of the reservoir) (%) and V_{\max} (L³) is the maximum volume of the reservoir.

2.6 The reservoir water quality model

The impacts of climate change on the water quality of Castanhão reservoir were estimated using the empirical Vollenweider model (OECD 1968), but with adjustments suggested by Chapra (2008). The expression below (Equation 3) was used satisfactorily by Lira *et al.* (2020) to consider the variation in volume, since the Brazilian semi-arid reservoirs vary widely in water level, in response to the spatial and temporal variability of rainfall and the effects of periodic droughts:

$$TP_{i+1} = TP_i \frac{V_i}{V_{i+1}} + \frac{(Q_{a,i}c_{a,i} - Q_{s,i}TP_i - k_iTP_iV_i)}{V_{i+1}} (t_{i+1} - t_i) \quad (3)$$

where TP is the annual average total phosphorus concentration in the reservoir (ML⁻³); c_a is the influent TP concentration in the reservoir (ML⁻³); k is the settling loss coefficient of TP (T⁻¹); and Q_s (L³T⁻¹) is the outflow from the reservoir. It is worth mentioning that the outflow represents all forms of water removal from the reservoir that can together carry the phosphorus, namely withdrawals, spill and groundwater flow (Chapra 2008). However, water loss from the reservoir through groundwater was ignored (Campos *et al.* 2016, Mesquita *et al.* 2020).

An intrinsic problem for the reservoirs in tropical semi-arid regions is the higher temperatures (~30°C) affecting the rate of consumption of phosphorus by biological activity and the water's viscosity, facilitating the sedimentation process of this nutrient (Castagnino 1982). As a result, this study used Equation (4), proposed by Toné and Lima Neto (2020), to consider the characteristics of the tropical semi-arid climate on the TP settling loss coefficient. This empirical formula is a correction of the expressions proposed by Vollenweider (OECD 1968) and Salas and Martino (1991), which were developed for reservoirs in a temperate (~10°C) and tropical (~20°C) climate, respectively:

$$k = \frac{4}{\sqrt{\tau_w}} \quad (4)$$

Table 1. Classification of trophic level based on the average total phosphorus (TP) concentration.

| Trophic level | TP concentration in reservoir (mg/L) |
|----------------|--------------------------------------|
| Oligotrophic | ≤0.026 |
| Mesotrophic | 0.027–0.052 |
| Eutrophic | 0.053–0.211 |
| Hypereutrophic | >0.211 |

where τ_w is the hydraulic residence time (T), representing the time necessary for the reservoir water to be renewed, defined here as the ratio between the reservoir's volume (L³) and the inflow (L³T⁻¹). This simple approach to estimate τ_w demonstrates a good accuracy for relatively well-mixed lakes (Pilotti *et al.* 2014). Consistently, Brazilian semi-arid reservoirs present very weak stratification contrasts from top to bottom (up to about 1–4°C), that are destroyed on a daily cycle (see Lima Neto 2019, Mesquita *et al.* 2020). It is also important to observe that Equation (4) was adjusted and validated by Toné and Lima Neto (2020) for a wide range of Brazilian semi-arid reservoirs. Additionally, it was also validated by Lima (2016) and Araújo *et al.* (2019) for reservoirs located specifically in the state of Ceará.

Because there was little data on the influent TP concentration of Castanhão, the correlation proposed by Rocha and Lima Neto (2020) was used, described by Equation (5), which relates the TP concentration and the streamflow of Castanhão. The data used to adjust the formula were related to the period 2012–2017.

$$c_a = 8.884Q_a^{-1.065} (R^2 = 0.91) \quad (5)$$

Equation (5) requires the streamflow to be in m³/s, thus presenting the influent TP concentration in mg/L. It was also necessary to restrict the domain of the expression in order to properly represent the physics of the phenomenon. So, a minimum value of 0.1 m³/s was considered, which corresponds to a maximum influent TP concentration of about 100 mg/L.

In this study, the trophic status classification used was based on the average TP concentration (Table 1); that is, it is the same system as that adopted by COGERH for their monitored reservoirs (Toledo *et al.* 1983, Klippel *et al.* 2020).

3 Results

3.1 Alterations to the reservoir's streamflow

Future average streamflow was projected using the SMAP model and datasets of five GCMs. Figure 4 shows the average streamflow for the baseline (2002–2014) and climate change conditions. The streamflow of Castanhão reservoir for the baseline was 67.80 m³/s. SSP5-8.5 displayed a stronger effect in terms of the relative changes of the streamflow compared to SSP2-4.5. SSP2-4.5 projected relative changes varying from -29% to 416% in the period 2015–2044, with the CanESM5 and MRI-ESM2-0 models showing the largest reductions. In the second period, for this same emission scenario, all climate models except CanESM5 projected an increase in the average streamflow, with relative changes varying from 12% to 456%. In the last period, CanESM5 predicted a drop of -16% in

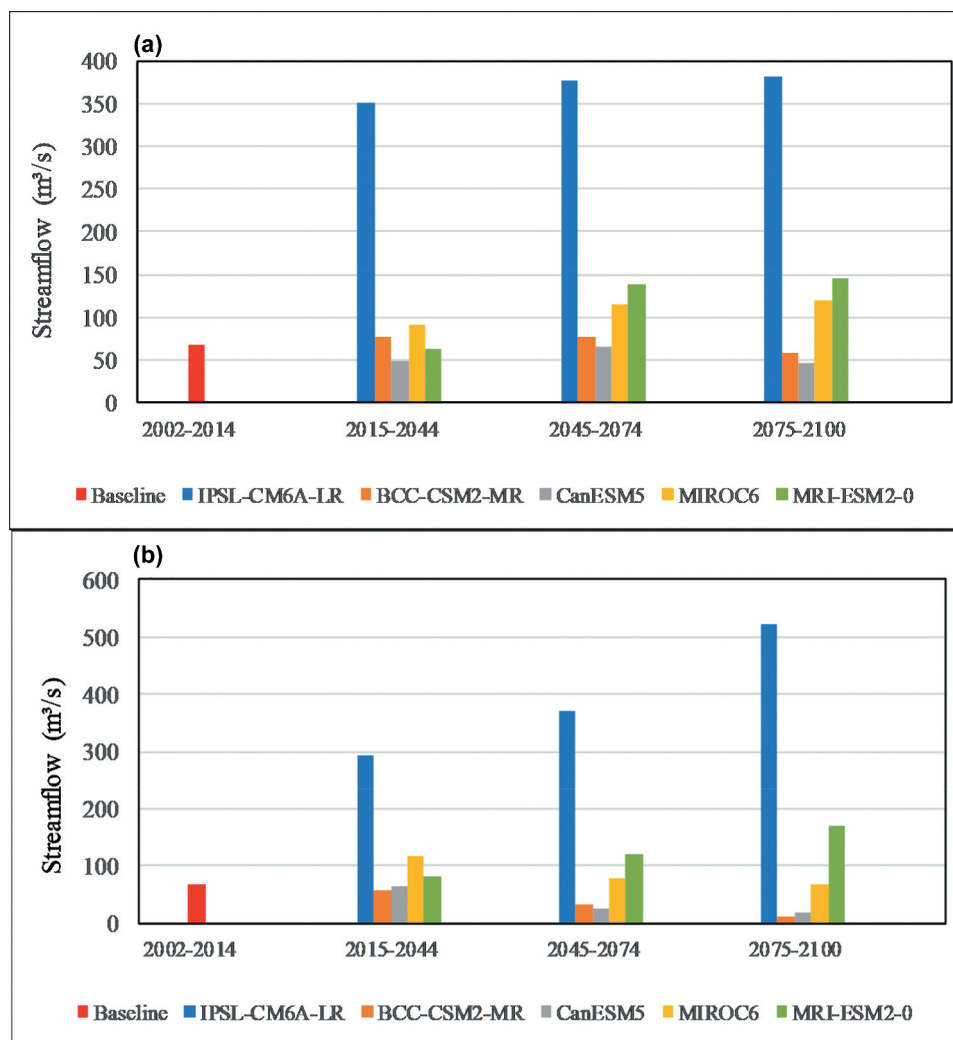


Figure 4. Average streamflow for conditions of baseline and climate change for (a) SSP2-4.5 and (b) SSP5-8.5 simulated by five different GCMs for the periods 2015–2044, 2045–2074 and 2075–2100.

relation to the baseline streamflow, while all other models projected positive relative changes, varying from 4% to 462%. For SSP5-8.5, BCC-CSM2-MR and CanESM5 predicted relative changes of –15% and –9%, respectively, during the 2015–2044 period, while the other three climate models forecast relative changes varying from 20% to 332%. For the period 2045–2074, IPSL-CM6A-LR, MIROC6 and MRI-ESM2-0 predicted an increase in the average streamflow, with relative changes varying from 15% and 449%, while BCC-CSM2-MR and CanESM5 projected decreases of –56% and –64%, respectively. In the period 2075–2100, the majority of the climate models predicted an increase in the average streamflow in relation to the baseline, with relative changes varying from 24% to 847%. However, BCC-CSM2-MR and CanESM5 projected significant drops in the average streamflow. The former predicted a drop of –84% and the latter a drop of –67%.

3.2 Effects on water balance and water level

The baseline percent volume was 55.10% (mean value of the reservoir for 2002–2014). No consistent trend was seen in the future projections of water level under SSP2-4.5 or SSP5-8.5

(Fig. 5). The maximum relative changes were similar in the two SSPs-RCPs, but SSP5-8.5 displayed more sharply negative relative changes. In SSP2-4.5, all GCMs except CanESM5 predicted a rise in the average percent volume of the reservoir in relation to the baseline in the three future periods. The positive relative changes varied from 3% to 76%, while CanESM5 projected decreases of –34%, –24% and –5% in the first, second and third period, respectively. For SSP5-8.5, in the period 2015–2044 the projections indicated an increase in the average percent volume of the reservoir varying from 2% to 42% in relation to the baseline. In the last two periods, most of the GCMs indicated an increase in the percent volume of the reservoir, but BCC-CSM2-MR and CanESM5 predicted significant reductions. The former model predicted a –48% decline in 2045–2074 and a –97% decline in 2075–2100, while the latter model predicted drops of –69% and –76% in the first and second period, respectively.

Figure 6 shows the average volume of the reservoir together with the representative average streamflow for the future periods assessed under the SSP2-4.5 and SSP5-8.5 scenarios. It was possible to infer that the drop in the percent volume of Castanhão was related to the decrease in the reservoir's streamflow (Fig. 6).

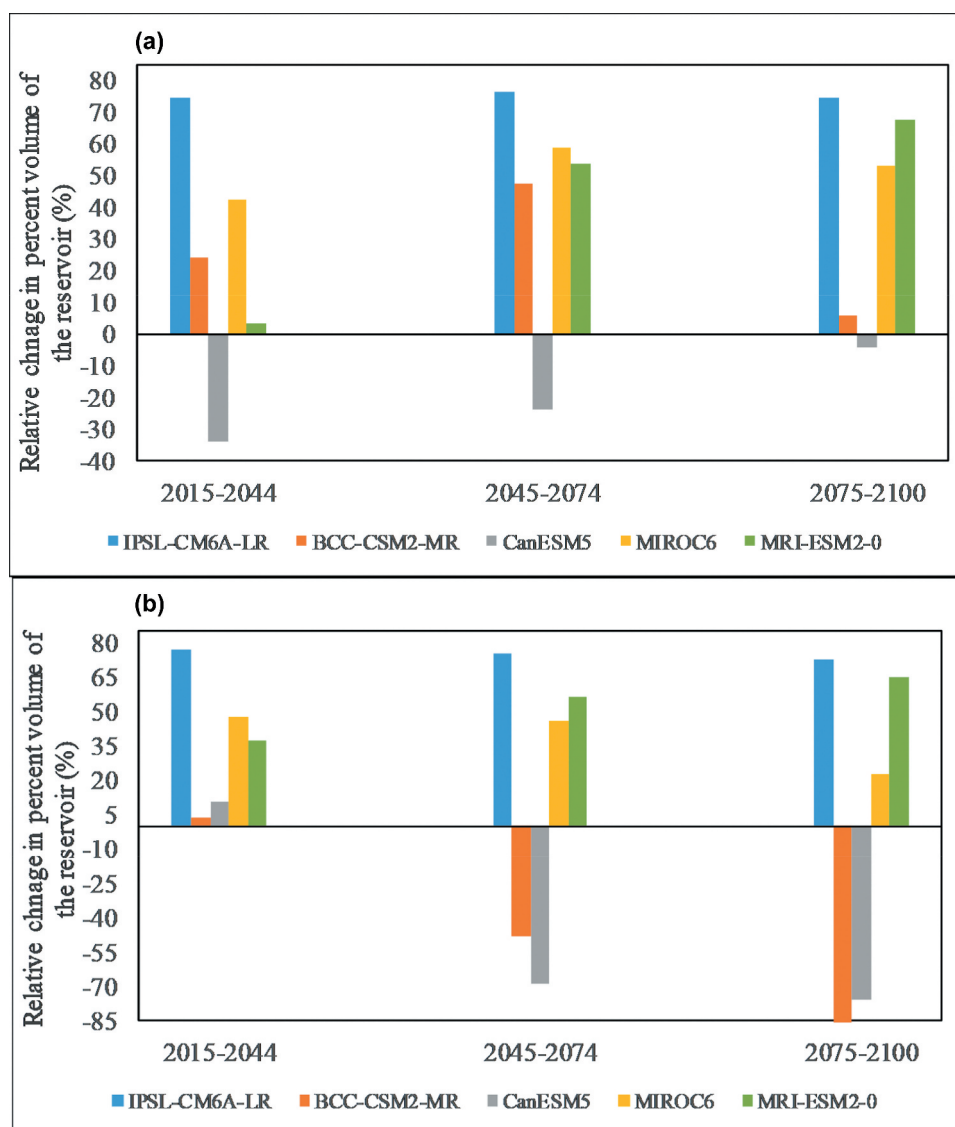


Figure 5. Relative change in percent volume of the reservoir for five different GCMs for 2015–2044, 2045–2074 and 2075–2100 for (a) SSP2-4.5 and (b) SSP5-8.5.

The most pessimistic scenarios associated percent volumes of the reservoir lower than 20% and annual average streamflow with decreases of more than 50% in relation to the baseline. Consistent with this, the CanESM5 model showed significant reductions in percent volume, and the BCC-CSM2-MR model predicted a higher possibility of prolonged drought in response to the reductions in the average streamflow. Furthermore, higher projections of the average streamflow than the baseline flow indicated an average percent volume above the baseline, with emphasis on IPSL-CM6A-LR, which predicted storage volumes close to the maximum volume of the reservoir, regardless of the period and emission scenario.

From a visual inspection of the results illustrated in Fig. 6, a characteristic mathematical behaviour was identified, with a percent volume increasing exponentially in one region, and another showing asymptotic behaviour. Thus, it adapted well to the monomolecular model, considering a parameterization using a half-life concept of time, since it had a more convenient interpretation when approaching the maximum percent volume (100%). Thus, in order to provide information regarding the

impact of climate change on the percent volume of Castanhão reservoir based on predicted streamflow, an expression was proposed that relates such variables [Equation (6), $p < 0.05$], encompassing the five different climate models, the two emission scenarios and the three assessed future periods:

$$V_p = 100 [1 - e^{-0.0148Q_a}] (R^2 = 0.94) \quad (6)$$

The monomolecular model parameters were determined using the method of ordinary least squares (OLS), considering the streamflow projections by the five different GCMs and the streamflow of the proposed model. The curve adjusted well to the data, as indicated by the high value of R^2 (0.94).

3.3 Response of TP concentration to climate change scenarios

3.3.1 Relative change in TP concentration in the reservoir

The future projection values of the average TP concentration in the Castanhão reservoir were compared with the

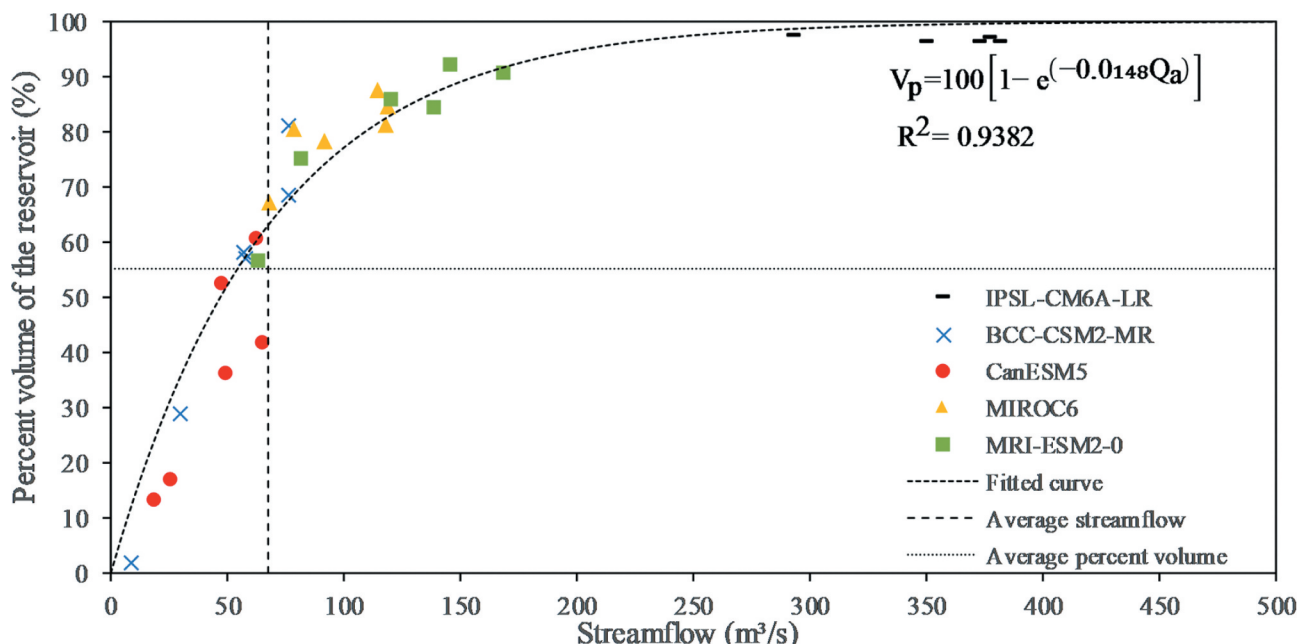


Figure 6. Relation between the percent volume and the streamflow forecast for Castanhão reservoir in climate change conditions for five different GCMs, considering scenarios SSP2-4.5 and SSP5-8.5 and periods 2015–2044, 2045–2074 and 2074–2100.

concentration (0.034 mg/L) during the 2008–2014 period, since the water quality records in the reservoir were only available for this period. Most GCMs indicated that the average TP concentration tends to increase (Fig. 7). Also, divergences were found in the projections of the average TP concentrations, both in magnitude (absolute values of relative change) and in sign (upward or downward trend). SSP5-8.5 projected a larger quantity of relative maximum variations of the average TP concentration than did the SSP2-4.5.

Under the SSP2-4.5, two GCMs indicated negative relative changes in the average TP concentration during the 2015–2044 period, while the other climate models predicted positive relative changes. In the period 2045–2074, all GCMs except CanESM5 indicated negative relative changes, varying from –67% to –19%. In the period 2075–2100, the MIROC6, MRI-ESM2-0 and IPSL-CM6A-LR models predicted negative relative changes, while the BCC-CSM2-MR and CanESM5 models predicted positive relative changes. In SSP5-8.5, BCC-CSM2-MR and CanESM5 predicted relative changes of 29% and 453%, respectively, in the period 2015–2044. In turn, MRI-ESM2-0, MIROC6 and IPSL-CM6A-LR predicted relative changes of –14%, –23% and –69%, respectively. In 2045–2074, significant increases were detected in the average TP concentration predicted from BCC-CSM2-MR and CanESM5. The other three GCMs predicted negative relative changes for this same period. In the last period, MRI-ESM2-0 and IPSL-CM6A-LR predicted relative changes of –45% and –57%, respectively. The other three GCMs predicted an upward trend of the TP concentration, where the BCC-CSM2-MR and CanESM5 models indicated a strong degradation of the water quality.

3.3.2 Trophic status of the reservoir in climate change scenarios

The combined behaviour of the percent volume and the TP concentration of Castanhão reservoir in the period from 2008 to 2019 is illustrated in Fig. 8. The TP concentration showed considerable variability, but it was possible to identify an upward trend in the reservoir's TP concentration over the years. The increase in TP concentration seemed to be in response to the drop in the reservoir volume, clearly based on a percent volume of around 20%. The linear regression analysis pointed in this direction, with a relatively high correlation value ($r = -0.67$). Consistent with this, in general the smaller volumes generated the largest TP concentrations, intensifying the trophic status of the reservoir and the eutrophication process as time went by. The annual average rate of increase in the TP concentration was 0.022 mg/L.

Based on TP concentrations, Castanhão reservoir was classified as hypereutrophic in the baseline period (2008–2014). In the climate change scenarios, the trophic status varied between oligotrophic and hypereutrophic (Fig. 9). SSP5-8.5 predicted further degradation of the water quality compared to SSP2-4.5, the latest period being the most pessimistic for the reservoir's water quality. Analyses revealed that around 40% of the average TP concentrations in the three periods studied were contained either in the eutrophic status or the hypereutrophic status, indicating the reservoir's eutrophication. The CanESM5 model predicted eutrophic status for the two SSPs-RCPs and three future periods. The BCC-CSM2-MR model projected eutrophication for all periods under SSP5-8.5, but in the first period only under SSP2-4.5. In contrast, the MRI-ESM2-0 model only projected eutrophication in the first period under SSP2-4.5. In other cases, the projections indicated oligotrophic or mesotrophic status.

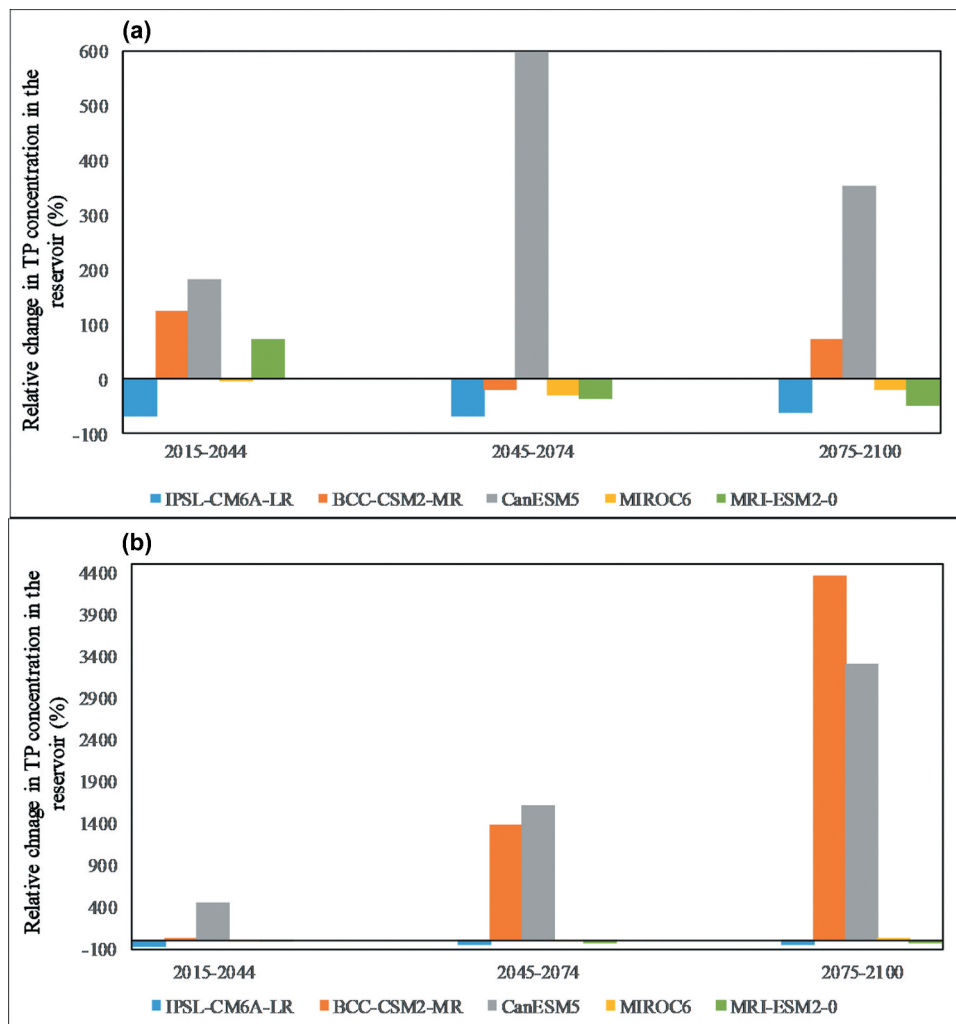


Figure 7. Relative change in average total phosphorus (TP) concentration in the reservoir for five different GCMs for (a) SSP2-4.5 and (b) SSP5-8.5 for periods 2015–2044, 2045–2074 and 2075–2100.

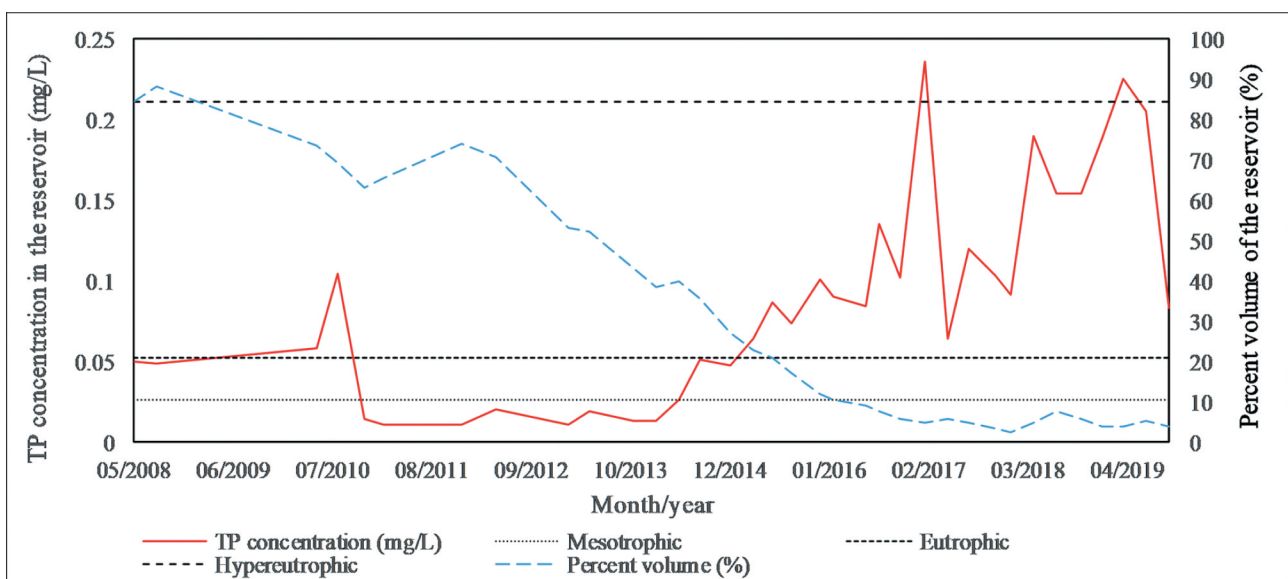


Figure 8. Relation between the average total phosphorus (TP) concentration and percent volume of Castanhão reservoir for the sampled period (2008–2019).

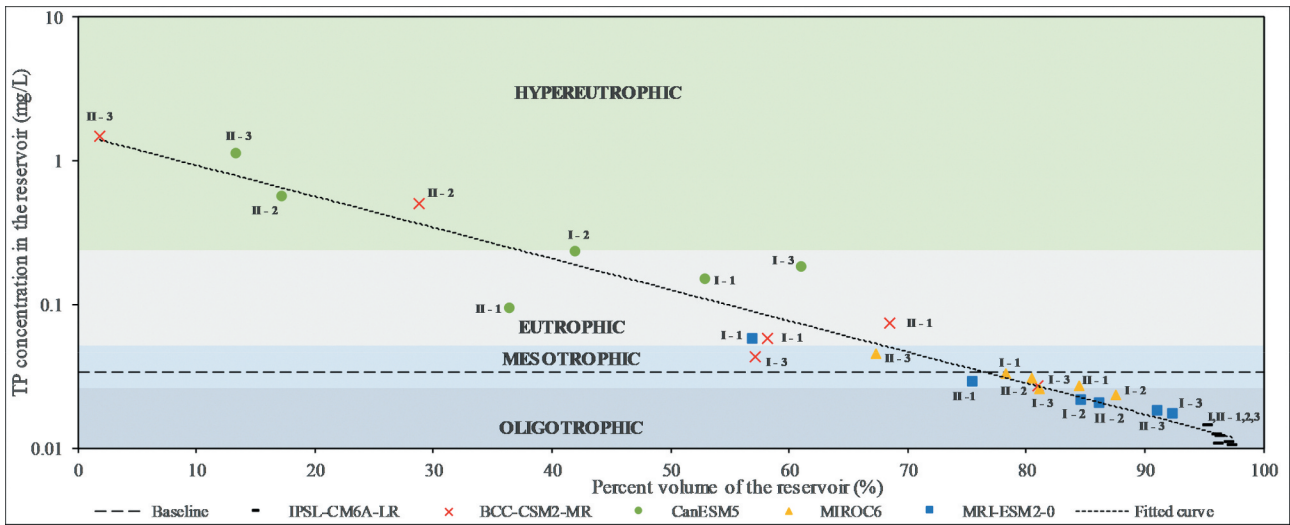


Figure 9. Projection of the representative average total phosphorus (TP) concentration (represents the three assessed periods from five different GCMs for Castanhão reservoir). The periods 2015–2044, 2045–2074 and 2075–2100 are represented by the Arabic numerals 1, 2 and 3, respectively, while SSP2-4.5 and SSP5-8.5 are represented by the Roman numerals I and II, respectively.

For climate forecasts, the linear regression analysis showed that the average TP concentration in Castanhão reservoir was related negatively to the percent volume ($R^2 = 0.94$). This result indicated that the drop in percent volume, due to the effect of prolonged droughts, exacerbated by climate change, intensified the reservoir’s trophic status, thereby increasing the possibility of eutrophication. Specifically, the highest average TP concentrations (>0.572 mg/L) were associated with percent volumes below 20% (compatible with the pattern observed in Fig. 8), while the maximum concentration (1.5 mg/L) was related to a percent volume of almost 0%. The inverse effect was also noted: the smaller average TP concentrations were related to high percent volumes (70%), such as the IPSL-CM6A-LR model projecting the smaller average TP concentrations.

Another expression [Equation (7), $p < 0.05$] was proposed relating the TP concentration and percent volume for Castanhão reservoir, based on the best adjustment to the

data, which could help decision makers in managing the impacts of climate change on the water quality of reservoir from its percent volume.

$$TP = 1.5286e^{(-0.05V_p)} (R^2 = 0.94) \quad (7)$$

As a comparison, Fig. 10 shows the relation between the streamflow and percent volume for another reservoir in Ceará (Orós). The purpose was to show the response of the percent volume to the projected streamflow, and the applicability of the procedure to generate the expression that relates these two variables, as an aid to decision makers. The same procedures that were applied to the Castanhão reservoir were used here, both for building the graphic result and for the concept of the expression. It is possible to also identify a clear relationship between the streamflow and percent volume of Orós reservoir, with similar graphic behaviour to that shown

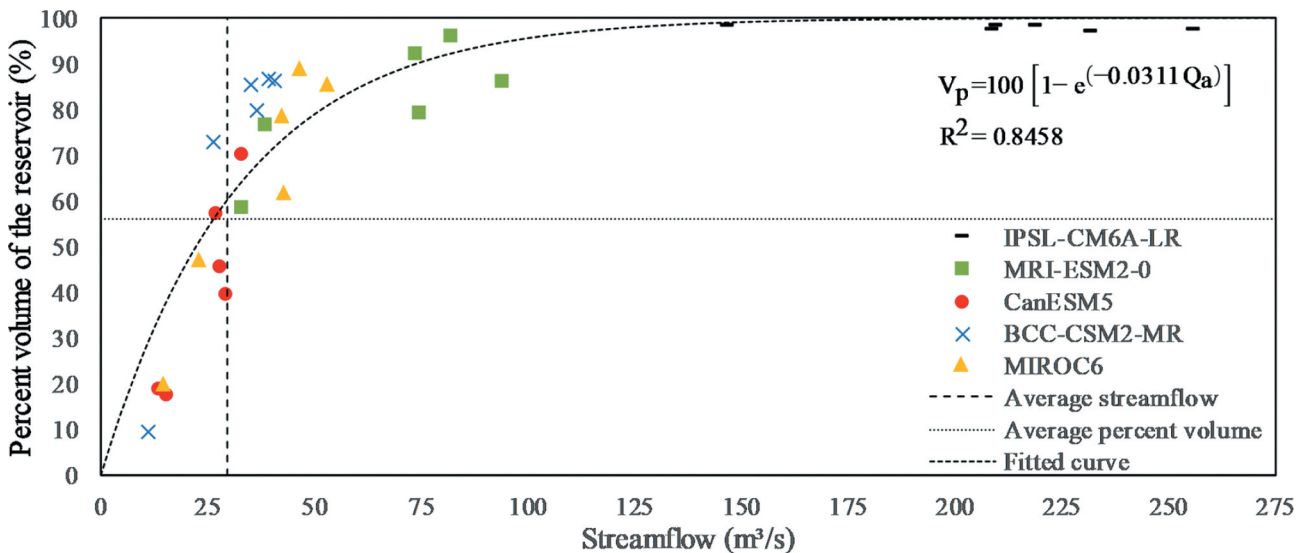


Figure 10. Relation between the percent volume and the streamflow forecast for Orós reservoir in climate change conditions for five different GCMs, considering scenarios SSP2-4.5 and SSP5-8.5 and periods 2015–2044, 2045–2074 and 2074–2100.

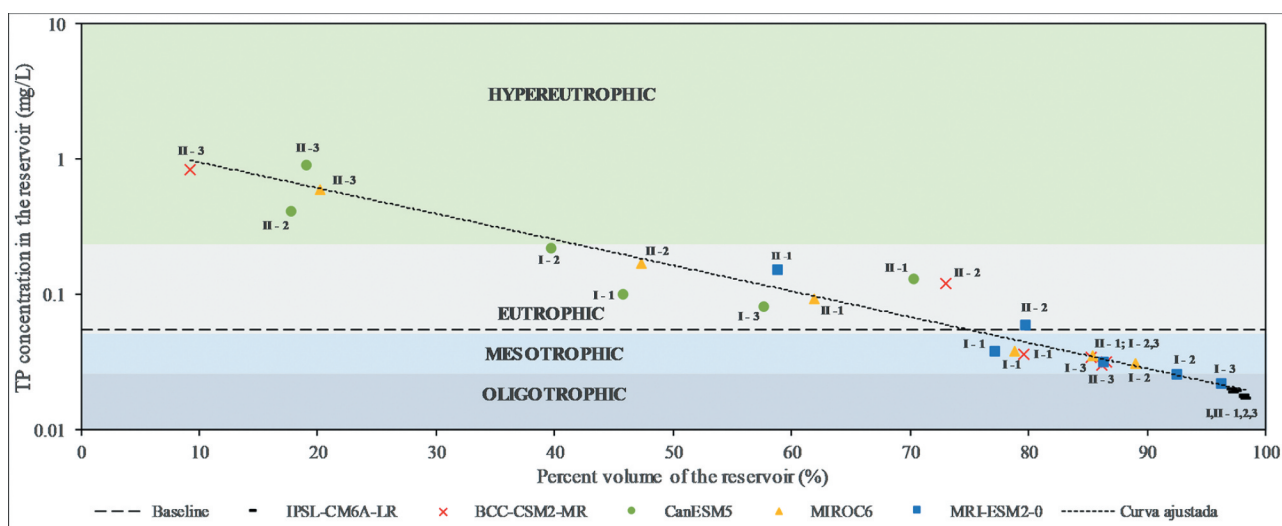


Figure 11. Projection of the representative average total phosphorus (TP) concentration (represents the three assessed periods from five different GCMs for Orós reservoir). The periods 2015–2044, 2045–2074 and 2075–2100 are represented by the Arabic numerals 1, 2 and 3, respectively, while the SSP2-4.5 and SSP5-8.5 are represented by the Roman numerals I and II, respectively.

in Fig. 6. The proposed expression for Orós reservoir satisfactorily represented the data, but with a lower determination coefficient than that for the Castanhão reservoir ($R^2 = 0.85$).

From Fig. 11, it was possible to also identify an increase in the TP concentration in Orós reservoir in response to the decrease in storage volume, reflected by a high value of the determination coefficient ($R^2 = 0.96$). The expression created based on the best adjustment of the future data of percent volume and TP concentration also had exponential behaviour. The findings for Orós reservoir reinforce that the reservoirs in the Brazil semi-arid region can be more prone to the impacts of climate change. Moreover, the results relating to Castanhão and Orós reservoirs suggest that the impacts of climate change on the reservoirs in the Jaguaribe River basin are similar, so it would be possible to jointly manage the impacts of climate change on the reservoirs in this region, extending the mitigating measures to all water bodies in the catchment area.

4 Discussion

This present study investigated the impacts of climate change on the hydrology and water quality of a large strategic reservoir (Castanhão) in Brazil's semi-arid region. Also, we discussed the increased eutrophication of tropical semi-arid reservoirs as a result of gradual decreases in the storage volume – namely, prolonged drought events. To project the future trophic status of Castanhão reservoir, five climate models were connected to the SMAP hydrological model, the outputs of which supplied the water balance equation and a complete mixing model to estimate the internal TP concentration under climate change scenarios.

4.1 Effects on the reservoir's streamflow

Strong divergences were noted in the streamflow projections for the five climate models under climate change scenarios. The observed divergences in sign and magnitude varied from -87% to 670% (Fig. 4). The uncertainties for the streamflow agreed with the results of projections made for the Jaguaribe

River basin (Krol and Bronstert 2007, Gondim *et al.* 2012, 2018). Fernandes *et al.* (2017) predicted streamflow variations from -70% to 110% over the periods 2040–2069 and 2070–2099. More recently, Estácio (2020) predicted relative changes varying from -75% to 400% , for the same reservoir as this study, during the 2025–2055 period.

Studies in other NEB regions have also presented divergences in future streamflow projections (Tiezzi *et al.* 2018, Silva *et al.* 2021). Silveira *et al.* (2016), for example, identified variations from -70% to 40% in the streamflow of the Brazilian hydro-power sector by the end of the 21st century. Uncertainties observed in the simulations are inherent to the projections of climate change impacts, which come from the highly sensitive climate systems and the actual imprecise nature of future climate projections, in addition to the uncertainties present in the down-scaling methods, choice of GCM, and climate data and GHG emission scenarios (Clarko *et al.* 2016, Kundzewicz *et al.* 2018). Accordingly, the uncertainties in the projections of the impacts of climate change on water availability have also been ascertained in several other studies for different regions around the world, and all of them stress the importance of using a multi-GCM approach to obtain more robust future projections (Yimaz and Imteaz 2011, Deb *et al.* 2018, Marhaento *et al.* 2018).

It is important to note that the present study focuses on the analysis of the impacts of climate change on hydrology. It should be noted that no major land-use change has been observed in the region over the last few decades, as reported by Lima Neto *et al.* (2011). On the other hand, Molina-Navarro *et al.* (2014) found that land-use management scenarios exhibit lesser effects (-7.6% to 7.3%) on the streamflow relative to climate change scenarios (3.4% to -48.7%). Couture *et al.* (2014) and Zhang *et al.* (2019) also identified less significant effects of land-use scenarios on hydrology compared to climate change scenarios. Marhaento *et al.* (2018) emphasized that it is still a challenge to accurately predict the future hydrological changes due to land-use and climate change, since there are various uncertainties, in particular associated with future climate change scenarios.

4.2 Effects on the reservoir's water level

In the baseline period (2002–2014), the volume of the reservoir was about 60%, but when inspecting the total period of water level records of Castanhão reservoir (see Fig. 8), the storage volume showed a gradual decrease, a consequence of the prolonged drought period (2012–2018) (Pontes Filho *et al.* 2020). In addition to the constant withdrawals for the supply, the volume of the reservoirs in the NEB gradually diminishes due to high evaporation rates and irregular rainfall. Braga *et al.* (2015) and Wada *et al.* (2013) illustrate these points clearly.

The water level projections indicated divergences (–96.7% to 76.56%) under the impacts of climate change. The same has been observed in other studies (Singh *et al.* 2011, Thorne and Fenner 2011, Molina-Navarro *et al.* 2014). Bucak (2018), for example, observed relative changes in projections ranging from –13% to 14%. However, prolonged droughts were identified as a result of climate change for part of the climate models, resulting in a sharp drop in the reservoir volume, and even achieving an almost zero volume in the most pessimistic scenario (see Fig. 6), which is comparable to the study carried out by Rocha Junior *et al.* (2018). 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).

With the knowledge that the streamflow influences the percent volume of the lakes and reservoirs, an expression was proposed that relates those two variables to Castanhão reservoir [Equation (16), $R^2 = 0.94$]. The expression managed to suitably capture the projections of the five different climate models for the aggregate scenarios.

4.3 Stream and reservoir simulations

The complete mixing model in this study was adapted to reservoirs of the semi-arid tropical climate (Toné and Lima Neto 2020), and considering the transient state and high variability of the storage volume in order to perform future projections of the TP concentrations that are more consistent with reality. This last consideration is an important characteristic of the water bodies in semi-arid basins (Lira *et al.* 2020). The use of the transient model compared to the permanent model has a strong impact on the TP concentration projection, since the permanent version ignores the residual TP concentration from one year to the next, by considering them separate (unpublished results). This fact may explain the low TP concentrations found by Molina-Navarro *et al.* (2014) and the consequently more optimistic trophic status (no projection in that study indicated eutrophication of the studied reservoir).

On the other hand, the water quality modelling procedures employed in this study should be used with caution, for three reasons. Firstly, the procedure for developing Equation (4) involves many hydrometeorological uncertainties and nutrient dynamics in the reservoir. Secondly, this correlation ignores the effects of extreme events of precipitation, heavy rainfall that admittedly could increase the nutrient transport to water bodies (Panagopoulos *et al.* 2011). However, over the past few decades, several studies have identified a close relationship between the direct runoff (surface + lateral) and nutrient

load in lakes and reservoirs (Sharpley *et al.* 1994, Zheng *et al.* 2004, Molina-Navarro *et al.* 2014). These results, and the fact that the streamflow of Castanhão reservoir coincides with the direct runoff on account of the crystalline soil, indicate that the use of the concentration-streamflow model (Rocha and Lima Neto 2020) may be a reasonable alternative for evaluating the impact of climate change on the water quality of reservoirs in the absence of nutrient load data (Bierzoza *et al.* 2018), and the consistent results of projections have shown their applicability. Finally, the structure of the complete mixing model adopted here does not reflect all the processes affecting TP concentration within the reservoir, such as the interaction with sediments deposited at the bottom, which can be an important source of internal TP load and cause water quality degradation (Moura *et al.* 2020).

4.4 Trophic status of the reservoir in climate change scenarios

The results of the projections of future TP concentrations showed a trend towards degradation of the water quality in Castanhão reservoir, although they varied in the response of the five different climate models. Divergences in terms of sign and magnitude in the projection of the average TP concentration and other nutrients representative of the water quality were also found in other studies (Couture *et al.* 2014, 2018, Nazari-Sharabian *et al.* 2019, Messina *et al.* 2020). Uncertainties in the projections of nutrient concentrations seem to have been spread throughout the climate, hydrological and water quality models (visual inspection of Figs 4, 5 and 7) (Trolle *et al.* 2011). Apparently, there was a cascade effect of the reduction in the streamflow and percent volume and an increase in the TP concentrations of the reservoir (Bucak 2018). This situation indicates the need to include in the adopted methodology the uncertainties propagated throughout the modelling (Chang *et al.* 2015).

Based on the average TP concentrations, almost half of the aggregate scenarios indicated eutrophication of Castanhão reservoir (see Fig. 9). The SSP5-8.5 scenario projected the highest increases in the annual average TP concentration, especially in the last two periods. Such results deserve particular attention, because the poor water quality has a direct influence on the quantitative aspect of the water resource, since polluted water is unfit to meet the domestic, industrial, recreational and farming requirements (Zhang *et al.* 2019).

In the studies of climate change impact on the water quality in lakes and reservoirs, the majority of studies available in the literature concentrate on water bodies in temperate and tropical climates (Arheimer *et al.* 2005, Komatsu *et al.* 2007, Thorne and Fenner 2011, Trolle *et al.* 2011, Molina-Navarro *et al.* 2014, Chang *et al.* 2015, Bucak 2018, Couture *et al.* 2018, Me *et al.* 2018, Nazari-Sharabian *et al.* 2019, Zhang *et al.* 2019, Messina *et al.* 2020). Only three of these studies predicted eutrophication of the water bodies, although all studies have pointed to the possibility of the intensification of trophic status. Messina *et al.* (2020), evaluating Auburn Lake, USA, projected the most pessimistic value in the hypolimnion layer (0.055 mg/L), but in the epilimnion the maximum value was 0.026 mg/L. Nazari-Sharabian *et al.* (2019), studying

a reservoir in Iran, projected values of 0.106 and 0.109 mg/L in the two most pessimistic scenarios, classifying the reservoir in question as eutrophic. Zhang *et al.* (2019) projected the most drastic increases of all studies available in the literature, where values reached 0.223 mg/L in the most pessimistic scenario, classifying the evaluated reservoir as hypereutrophic. Comparing the TP concentrations in these studies with the most pessimistic values of the study herein (see Fig. 9), there is further evidence that tropical semi-arid reservoirs may be more prone to eutrophication as a result of the negative impacts of climate change (Coppens *et al.* 2016).

Results reported by other authors regarding the internal TP concentration of reservoirs around the world validate the significance of the maximum concentrations found in this research for the most pessimistic aggregate scenarios. Jensen *et al.* (2006), investigating the dynamics of phosphorus of 16 eutrophic lakes in Denmark, found average TP concentrations varying from 0.094 to 0.963 mg/L. Rocha Junior *et al.* (2018) reported average TP concentrations higher than 1.0 mg/L for most tropical reservoirs assessed (5 out of 8) during the driest period of the year in one of the analysed sub-basins, which was in a region with a semi-arid climate in the Brazilian state of Rio Grande do Norte. This panorama is consistent with Me *et al.* (2018), who stated that climate change may intensify the various forms of pollution in river basins.

This study found relations that suggest the high TP concentrations in Castanhão reservoir were related to the interference of climate change with two variables: decreases in the reservoir's streamflow and storage volume (see Figs 6 and 9). This result confirms the hypothesis that the drop in storage volume intensifies the trophic condition of the reservoirs due to the impacts of climate change (Rocha Junior *et al.* 2018). This occurs because a decrease in the storage volume of these water bodies increases the internal nutrient concentration (Jeppesen *et al.* 2015, Wiegand *et al.* 2021). On the other hand, the scenarios that projected a decrease in the streamflow can also contribute by increasing the nutrient concentration in the reservoir, since the drop in runoff diminishes the dilution capacity of the transported pollutants (Zwolsman and van Bokhoven 2007, Araújo *et al.* 2019).

In this context, the negative effect of prolonged droughts on water quality seems to be more significant for reservoirs in the tropical semi-arid regions, since they have decreased storage volume and strong streamflow seasonality (Mesquita *et al.* 2020, Wiegand *et al.* 2021). These results are particularly important, since the complete mixing model used in the study herein was expressed directly or indirectly as a function of these characteristics (Equation 3), as the TP decay coefficient and the hydraulic residence time are described as functions of streamflow and storage volume.

A formula was also proposed to relate the TP concentration in the reservoir to its percent volume and, consequently, its trophic status [Equation (18), $R^2 = 0.94$]. These mathematical expressions can act as a tool for the sustainable management of the water quality of Castanhão reservoir under climate change scenarios, since they help anticipate the impacts of climate change on the hydrology and water quality of the reservoir. Also, the procedures adopted to develop the aforementioned mathematical expressions have been consistent when applied

to another reservoir in the region (Orós reservoir), suggesting the applicability of the procedures to help manage the reservoirs in the Brazilian semi-arid region under climate change.

4.5 Risk of cyanobacterial blooms

Another point worthy of attention is that eutrophication and climate change favour the proliferation and growth of cyanobacterial blooms (Paerl and Huisman 2009, O'Neil *et al.* 2012). We can therefore say that the aggregate scenarios that projected eutrophication of Castanhão reservoir suggest the favouring of cyanobacterial blooms (Carvalho *et al.* 2013, Bucak 2018). This is why it is necessary to stress the urgent need to control the phosphorus input in the reservoir, largely considered able to neutralize the eutrophication of water bodies (Schindler *et al.* 2016). Such a suggestion becomes even more necessary due to the low coverage and sewage treatment of the sub-basin in question. Thus, several studies have indicated the need to reduce the external nutrient loads, to prevent high concentrations of pollutants in the lakes and reservoirs and a consequent bloom of cyanobacteria, as one of the measures against intensifying global warming (Kosten *et al.* 2012, Nielsen *et al.* 2013, Bucak 2018, Nazari-Sharabian *et al.* 2019). However, in addition to measures for controlling land use, stricter restrictions are required for water withdrawal, and the operation of the reservoir must consider qualitative aspects as one of the goals to be achieved (Shokri *et al.* 2014, Ehsani *et al.* 2017, Azadi *et al.* 2019, Nazari-Sharabian *et al.* 2019, Feldbauer *et al.* 2020).

5 Conclusions

The effects of climate change on the trophic status of Castanhão reservoir were investigated using a combination of climate, hydrological and water-quality models. The results show strong uncertainties in the future projections of the variables assessed, suggesting the spread of uncertainties over the stages of the integrated approach. However, some of the projections raised warnings related to Castanhão reservoir's water quality. Climate change has also evidenced the capacity to affect two of the reservoir's major variables: streamflow and reservoir volume. The drop in storage volume was related to the reduced streamflow. This drop impacted the self-purification of the river that feeds the reservoir, causing further nutrient concentration flow in the water body. On the other hand, the decrease in volume implied an increase in the reservoir's internal TP concentration. As a direct impact, intensification of the trophic status was projected for half the aggregate scenarios, compared to the baseline. Also, eutrophication of the reservoir was detected in 40% of the aggregate scenarios. Deterioration of the water quality proved to be more serious in the last evaluated period (2075–2100) for SSP5-8.5. It was found that the drought events could be exacerbated under climate change scenarios, especially at the end of the century for SSP-8.5, increasing the internal TP concentration. Similar results were also obtained for the other large reservoir (Orós) considered in the present study. The above suggests that water bodies in this region could be more vulnerable to the eutrophication phenomenon under climate change scenarios compared to other regions around the world,

since they already suffer from gradual reductions in storage volume and recurrent droughts. The results of this study can help decision makers in developing mitigating measures to combat the impacts of climate change on the water quality of the reservoirs of the Brazilian semi-arid region.

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Disclosure statement

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