



Phosphorus mass balance and input load estimation from the wet and dry periods in tropical semiarid reservoirs

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Abstract

The dynamics of total phosphorus (TP) in 18 strategic reservoirs of the high-density reservoir network of the Brazilian semiarid was evaluated during the wet and dry periods for the past 12 years. Seasonal overlying concentrations presented no significant differences for about 90% of the reservoirs ($p > 0.05$). This was attributed to a trade-off between the hydrological/limnological processes occurring in the two seasons. Then, a transient complete-mix mass balance model was applied with particular adaptations for the tropical semiarid reservoirs to estimate the TP load for each season. Because of the relatively well-mixed conditions and high hypolimnetic dissolved oxygen concentrations during the wet season, the wet load was assumed to represent the external TP load. On the other hand, because of the absence of reservoir inflow during the dry season, phosphorus release under anoxic sediment conditions and wind-induced resuspension under shallow water depths, the dry load was assumed to reflect the internal TP load. The maximum external loads were related to peak inflows, notably after drought periods. Consistently, the largest internal loads were obtained during the drought periods, when the reservoirs were shallower and more prone to phosphorus release and resuspension. By comparing the impact of the two input load types, the wet period load was predominant in 72% of the reservoirs. The areal phosphorus loads ranged from 0.66 to 7.29 gP m² year⁻¹, which were consistent with the literature, despite the very high density of reservoirs. Finally, power-law curves including data for all studied reservoirs were adjusted between the dry period load and volume, dry and wet period loads, wet period load and inflow, and total load and catchment area, resulting in satisfactory R^2 (0.84–0.98).

Keywords Total phosphorus · Phosphorus dynamics · Internal and external loads · Eutrophication · Water quality modeling

Introduction

The reduction of phosphorus (P) loading has been the major effort to deal with the eutrophication issue in lakes (Le Moal et al. 2019). Total P in water consists of a variety of organic and inorganic forms (Doan et al. 2018), in which the processes within the lake are also an important source of contribution (Nürnberg 2009). Additionally, lake's morphometry, climatic conditions, oxygen concentration, and macrophyte presence play an important role on P dynamics (Kowalczevska-Madura et al. 2019; Seitz et al.

2020; Wiegand et al. 2021), especially on its spatial and temporal variability (North et al. 2015).

A broader distinction regarding P origins is widely accepted: phosphorus carried through rivers to downstream lakes or reservoirs is called external P loading (Song et al. 2017), which may be further divided into point and non-point sources (Bowes et al. 2008). In contrast, P released from sediments within the waterbody is known as internal loading (Nikolai and Dzialowski 2014). P-enriched sediments are a result of a long-term accumulation process from P entering the lake. Then, at some extent, there is a relation between these two sources once the external one origins internal nutrient recycling. The formidable challenge, though, is to track lake water P and distinguish its origin from internal or external sources (Nürnberg et al. 2013).

Commonly, external load represents a higher percentage in an annual P budget, and its relevance have formed the basis for classic predictive models such as the one of Vollenweider (1968) (Lepori and Roberts 2017). The majority of P that

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comes to a lake ecosystem, however, is usually stored in the bottom sediment (Kiani et al. 2020), which in appropriate conditions returns to the water column (Moura et al. 2020b). P releasing from sediments results from physical and/or biogeochemical mechanisms that operate on different temporal and spatial scales in a complex process (Orihel et al. 2017; Søndergaard et al. 2003; Araújo et al. 2019). Therefore, internal loading might pose a high risk of becoming an additional P source which contributes to the total in-lake P bioavailability and to the deterioration of the trophic state and water quality (Doan et al. 2018).

For tropical semiarid regions, such as the Brazilian Northeast, most water supply reservoirs are already eutrophic or hypereutrophic, which turns the P pollution issue a great concern for water resources management (Lopes et al. 2014; Pacheco and Lima Neto 2017; Lacerda et al. 2018; Lira et al. 2020; Raulino et al. 2021; Rocha and Lima Neto 2021). Additionally, the reservoirs are under two periods marked by a clear seasonality: the dry and wet one. The dry period extends to almost the entire second semester of the year and has an inflow virtually nil (Costa et al. 2020). In this region, the internal load production is expected to be stronger in the dry season, as hypolimnetic dissolved oxygen usually falls below 1.0 mg L^{-1} (Souza Filho et al. 2006), the water volume decreases and the wind speed intensifies (Mesquita et al. 2020). Under these effects, anoxia-induced P release and wind-induced resuspension are highly likely (Moura et al. 2020b). Additionally, only a few regions (mostly arid or semiarid environments) present intermittent rivers in which is possible to have a controlled period with the minimal interference of external inputs on P modeling. Hence, an analysis focusing on these two distinct periods (wet and dry seasons) might contribute to the understanding of TP dynamics and the role of internal and external TP load in waterbodies of dryland areas.

Despite the importance of internal loading for lake modeling, its quantification and/or comparison to external loading is seldom performed, mainly in semiarid aquatic ecosystems. External loading is normally evaluated from the product of flow rate with measured or modeled P concentration at the lake inlet (Bowes et al. 2008). As for internal load quantification, there are several ways to determine it depending on data availability (Nürnberg et al. 2012), such as determination from hypolimnetic P increases, regression analysis, time-dynamic modeling, estimates from anoxic active area, and mass balance approaches (Nürnberg 2009). Widely applied, mainly when calculating multiyear averages (Nürnberg et al. 2012), is the P load estimation by constructing a whole-lake mass balance accounting for a global sedimentation rate (Orihel et al. 2017). The issue of P budget from measured concentration, however, is the difficulty to distinguish between different sources (Nürnberg et al. 2012). Meantime, a mass balance analysis in a controlled period when the inflow is nil, such as the dry period of the Brazilian semiarid, may allow the

quantification of the internal load as the main TP input. The climatic conditions imposed upon the waterbodies in this region, such as a diurnal mixing cycle (Lira et al. 2020; Mesquita et al. 2020), weak stratification patterns (about $1\text{--}5^\circ\text{C}$) (Lacerda et al. 2018), and low depths due to drought events (Wiegand et al. 2020), support the application of parsimonious models to quantify TP load production.

Thus, the objective of this work was to develop a novel methodology based on a transient complete-mix mass balance model to estimate the wet and dry period TP loads to strategic water supply reservoirs in the Brazilian semiarid region. Specifically, the goals were (i) to evaluate the dynamics of seasonal and interannual epilimnion and average water column TP concentration under the influence of the wet and dry periods, (ii) to model and assess circumstantial evidences for the large likelihood of internal loading, (iii) to compare estimated internal loads in the context of external loading, and (iv) to analyze and propose general correlations between TP loads and reservoir/catchment characteristics. The results from this study will improve the knowledge of the limnology of tropical semiarid reservoirs, and the proposed model/correlations will be potential tools to promote sustainable integrated water management in dry lands.

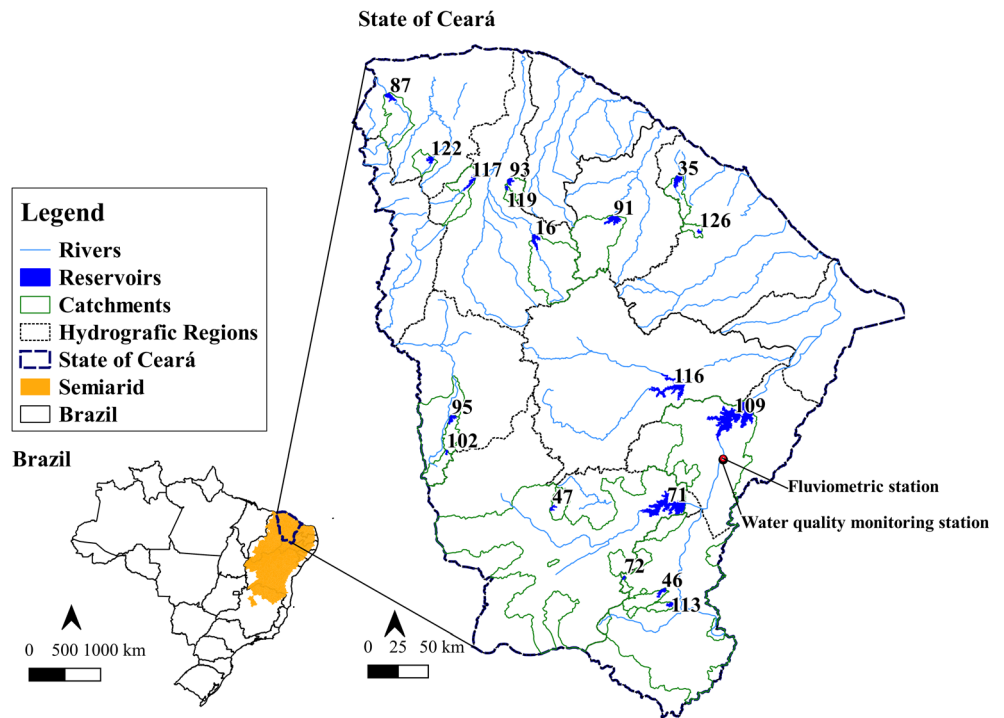
Methodology

Study area

The study area covers eighteen monitored water supply reservoirs in the State of Ceará, Brazil, presented in Fig. 1. Table 1 details their specific location and general characteristics. These reservoirs are scattered in the twelve hydrologic regions in which the State of Ceará is divided for water resources management. The combined area of their catchments represents about 59% of the state's area, and their volume reach a total accumulated capacity of 10.19 km^3 . The shallowest reservoir is Colina (maximum depth of 12 m), while the deepest is Castanhão (maximum depth of 71 m deep). These water bodies support the network that supplies water for human, industrial, and agricultural uses. On average, the reservoirs have a depth of 23.85 m. However, due to the 6-year drought event within the study period (Moura et al. 2020a), this average dropped to 13.35 m.

Land use in the catchments is dominated by managed grasslands with a spread anthropogenic presence in which a variety of animal husbandry is carried out, including fish farming in some reservoirs. Agricultural land with irrigated crop production can be found in Jaguaribe river basin, while dispersed rural population practices are primarily subsistence agriculture and plant extraction. With regard to climate, rainfall vary from $605.07 \text{ mm year}^{-1}$, in the Colina reservoir catchment to $1378.62 \text{ mm year}^{-1}$ in the Itauna catchment. The rivers which supply these reservoirs are intermittent, with inflow occurring only during the rainy

Fig. 1 Location of the eighteen studied sites in the State of Ceará-Brazil, whose description is presented in Table 1



season (January to July). From 2012, almost the entire State of Ceará has faced a prolonged drought period that led to a continuous reduction in the reservoirs' volume (Wiegand et al. 2020).

A more detailed description of the geology, geomorphology, and land use of the studied catchments can be found in CEARÁ (2020b).

Table 1 Physical characteristics of the studied reservoirs, their catchments, and the period of available water quality data

ID	Reservoir	Main river	Catchment area (km ²) ^a	Mean surface area (km ²) ^a	Mean depth (m) ^a	Data period	Inventory date ^b
16	Edson Queiroz	Groaíras	1778	7.90	17.32	2008–2019	2011
35	Sítios Novos	São Gonçalo	446	4.35	10.96	2008–2019	2008
46	Rosário	Rosário	337	3.83	10.40	2010–2019	2011
47	Rivaldo de Carvalho	Rivaldo de Carvalho	318	0.68	9.12	2008–2019	2011
71	Orós	Jaguaribe	24,538	61.34	6.51	2008–2019	2011
72	Olho D'água	Machado	72	1.18	12.52	2008–2019	2008
87	Itauna	Timonha	781	11.48	7.30	2011–2019	2011
91	General Sampaio	Curu	1582	10.10	17.54	2008–2019	2011
93	Forquilha	Oficina	191	3.05	7.71	2008–2019	2008
95	Flor do campo	Poti	663	3.82	10.96	2010–2019	2011
102	Colina	Poti	363	1.31	6.00	2008–2019	2009
109	Castanhão	Jaguaribe	44,800	123.14	35.50	2008–2019	2011
113	Cachoeira	Caiçara	143	1.92	12.00	2008–2019	2011
116	Banabuiú	Banabuiú	14,243	18.86	28.44	2008–2019	2011
117	Ayres de Souza	Jaibaras	1102	6.94	14.45	2010–2019	2009
119	Arrebita	Sabonete	79	1.50	9.10	2008–2019	2011
122	Angicos	Juazeiro	286	5.98	9.45	2008–2019	2011
126	Acarape do Meio	Pacoti	210	1.50	15.04	2008–2019	2008

^aCEARÁ (2020a)

^bCEARÁ (2020b)

TP load estimation

Considering the available data for this study, the method used for the internal P loading estimation was a complete P budget. The basic assumption for the load estimation process considered that during the wet season (high inflows) prevails external loads, while the internal load is dominant during the dry season (absence of inflows). However, it is acknowledged the possible existence of the internal load, even in small percentage during the wet season or possible external load contribution through point source, such as eventual animal's access to the waterbody, during the dry season. Then, to avoid a generalization, the loads estimated in the rainy season will be referred as the wet period load and those estimated for the dry season as dry period load, while they intend to represent the external and internal loads, respectively. This assumption is considered adequate since during the wet season, the well-mixed behavior in the reservoirs is favored by the inflow as well as a reduction in any stratification pattern (Lima Neto 2019). Moreover, as the reservoirs have rural catchments, significant external P input is expected from runoff during the wet period. On the contrary, during the dry season, the inflow is negligible, the water level is lower, and the wind velocity is higher (Wiegand et al. 2021), which enhance physical processes such as P resuspension in addition to biogeochemical ones. Furthermore, it is widely reported the prevailing of external load during the rainy period and the internal loading during the dry period in the study region and other semiarid environments (Freire et al. 2009; Coppens et al. 2016; Cavalcante et al. 2018; Barbosa et al. 2019).

Total phosphorus model

The transient complete-mix model presented in Eq. (1) was designed to predict the average TP concentration in hypothetically well-mixed waterbodies (Vollenweider 1968; Chapra 2008). The model involves parameters related with the lake morphometry, water balance, and nutrient dynamics. It was applied as a calibration process of the load for time intervals of, at most, 4 months, in which the initial and final TP concentrations were available. The remaining parameters were calculated as an average over the period between the TP measurements. TP concentration, morphometric and water withdrawal data were provided by the Water Resources Management Company of the State of Ceará (COGERH), for the eighteen studied reservoirs (Ceará 2020a). Regarding the water quality, TP measurements are usually collected four times a year, twice per semester, generally at the beginning and at the end of the wet and dry periods. Thus, in this study, the data collected from January to July were considered representing the wet season, while the data from August to December were considered as representative of the dry one.

$$TP(t) = TP_o e^{-\left(\frac{Q}{V}+k\right)t} + \frac{W}{Q+kV} \left[1 - e^{-\left(\frac{Q}{V}+k\right)t}\right] \quad (1)$$

In which $TP(t)$ is the total phosphorus concentration at a specific time (kg m^{-3}); TP_o is the total phosphorus concentration at the initial time (kg m^{-3}); t is the elapsed time (year); V is the reservoir volume averaged over the elapsed time (m^3); W is the TP load (kg year^{-1}); Q is the released flow ($\text{m}^3 \text{ year}^{-1}$); k is the TP settling loss rate (year^{-1}).

The application of Eq. 1 consisted of taking paired measurements of surface TP concentration [TP_o and $TP(t)$], the elapsed time between these measurements (t), and the mean parameters of the reservoir for this time interval (V , Q , and k) to estimate the average TP load (W). For the paired TP concentration measured during the wet season, the fitted W refers to the load of the wet period. Similarly, from TP concentrations measured during the dry season, W refers to the load of the dry period. This process was applied whenever there was available data for both periods (wet and dry) among the years presented in Table 1. The results, then, were converted to a monthly average. The areal phosphorus load was also obtained from the division of each estimated load by the mean lake surface area of the same time interval. The surface area was obtained through level-area-volume curves available in CEARÁ (2020a).

The TP load estimation was performed to identify and differentiate the roles of the wet and dry seasons in the input loading production. However, in larger reservoirs such as Castanhão, periods of low hypolimnetic dissolved oxygen ($< 2 \text{ mg L}^{-1}$) are observed during the rainy season (Santos et al. 2016). This suggests the occurrence of P release during the rainy period. Meantime, since in this period most of the total load is external due to high inflow, the internal load contribution to the budget during the rainy season is expected to be small (Freire et al. 2009). Furthermore, although internal load is typically ortho-phosphate release, its estimation from TP concentration was originally proposed by Nurnberg and LaZerte (2001), accounting primarily for the unavailability of P speciation data. It was also highlighted that P speciation, such as the analysis of ortho-phosphate as DRP, does not necessarily lead to a reliable quantification of internal load. Only in anoxic hypolimnia with elevated TP concentrations DRP determination may be used to accurately quantify internal load (Nürnberg 2009). Additionally, the internal load quantification as a mass of total phosphorus has been widely applied (Nürnberg 2009, 2012, 2013; North et al. 2015; Horppila et al. 2017).

Settling loss rate (k) and retention time (RT)

The TP model applied in this study integrate the processes of P removal from the water in the parameter k , a global decay coefficient which accounts for the average P settling. The

empirical relationship that correlates k with the theoretical hydraulic residence time (RT) presented in Eq. (2) was a workaround to the difficulty of estimating k experimentally. Moreover, it was adjusted and validated by Toné and Lima Neto (2019) for a wide range of Brazilian semiarid reservoirs and also validated by Lima (2016) and Araújo et al. (2019) for reservoirs located specifically in the State of Ceará. It is noteworthy that similar empirical relations with k varying with the inverse of $RT^{1/2}$ were also developed for temperate and tropical lakes (Vollenweider 1976; Salas and Martino 1991). However, this correlation (Eq. 2) intended to consider the effect of the higher water temperature of the Brazilian semiarid reservoirs (~30°C), as compared to those for temperate (~10°C) and tropical (~20°C) lakes. Higher water temperature leads to a combined effect of increasing P consumption by algae and decreasing water viscosity, then favoring higher phosphorus sedimentation rates (Toné and Lima Neto 2020). Equation (2) can also be obtained by applying the equations accounting for algae consumption and water viscosity (see Castagnino 1982) to convert the values of k from temperate or tropical lakes to semiarid ones. Therefore, it was assumed to be reliable for the purposes of the present study.

$$k = \frac{4}{RT^{1/2}} \tag{2}$$

The real residence time, depending on reservoir morphology and hydrodynamics (Castellano et al. 2010), was replaced by the theoretical hydraulic residence time (RT). It was considered a consistent assumption since it is in accordance with the complete-mix hydraulic behavior adopted and has demonstrated to have good accuracy for relatively well-mixed lakes (Pilotti et al. 2014). The RT was calculated as presented in Eqs. (3) and (4) for the wet and dry periods, respectively. The common definition of residence time (Eq. 3) accounts for continuous river flow. However, as the rivers in the study area are intermittent, the replacement of the inflow (I) by the sum of the rates of released (Q) and evaporated (E) flow was performed when modeling a time interval during the dry conditions.

$$RT = \frac{V}{I} \tag{3}$$

$$RT = \frac{V}{Q + E} \tag{4}$$

Water quality and water balance data

Epilimnion TP concentration and chlorophyll-a measurements consisted in the most complete dataset available. Samples were collected about four times a year close to the reservoir

dam or the floating pumping station, and then analyzed according to APHA (2005). The measurements of TP in the hypolimnion, however, represented a shorter dataset and were used to perform statistical analysis and evaluate the mixing hypothesis adopted as well to support the use of TP concentration in the upper layers as a reference to estimate the input load. With regard to TP load data, COGERH has also elaborated an environmental inventory covering the catchment of each studied reservoir for the year shown in Table 1. Since they are highly costing and time demanding, they were elaborated only once. The methodology applied estimated the annual TP load produced by each catchment based on the export coefficient modeling (ECM) approach (Johnes 1996). Details on the calculation process of this reference load are available in CEARÁ (2020b).

COGERH also provided the water level measurements and level-volume curves, used to obtain the morphometric data and the water balance data (inflow and released flow) on a monthly basis. Particularly for the inflow, since it is obtained from water balance, it accounts the water coming from all sources to the water body. Then, possible P-rich groundwater occurring during the wet period is incorporated in the model as external P sources, according to Orihel et al. (2017). Lastly, the evaporated height was quantified from the climatological normals of the closest climatological station to each reservoir (Brazil 2020).

Comparison of different P modeling approaches and model validation

The validation of the estimated loads was performed through a correlation analysis between the mean modeled annual TP load and the reference load available by CEARÁ (2020b). Moreover, as the Castanhão reservoir features two additional measured water quality and quantity datasets, the validation specifically of the wet TP load estimated for this reservoir was performed. An active fluvimetric station is located in its main river allied with a water quality monitoring point in which riverine TP concentration is measured (see Fig. 1). The proximity between the fluvimetric station and the water quality sampling point (less than 50 m) and of those two reservoirs (less than 24 km) allows the estimation of the wet TP load from a flow-concentration approach (Bowes et al. 2008). This load was estimated by multiplying the measured riverine TP concentration ($kg\ m^{-3}$) and the daily average flow ($m^3\ s^{-1}$) observed in the fluvimetric station for the same day of TP sample. Then, these loads were correlated with the ones obtained according to Eq. (1), for the same time period.

Statistics and uncertainty analysis

The load estimation process might arise uncertainties from the hydrological parameters and water quality data (Hollaway

et al. 2018). Initially, an outlier analysis of the TP concentration and chlorophyll-a data was performed. For the TP data, it was considered the limiting value of $4000 \mu\text{g L}^{-1}$ for TP concentration in wastewater (Sperling 2007), in which values over this limit were excluded. Additionally, the coefficient of variation of the estimated loads was calculated for each reservoir, as well as the bias existing between the modeled loads and the reference load. A further quality analysis of these statistical parameters in comparison with the available literature for TP load estimation was performed. Finally, a research was carried out to gather mean error values for the TP load estimated by the ECM methodology. The value of 31% was the maximum reported in the searched literature (Johnes 1996; Ding et al. 2010; Matias and Johnes 2012; Delkash and Alfaraj 2014; Greene et al. 2015; Tsakiris and Alexakis 2015). Then, it was used to discuss and evaluate the variations of the reference load in comparison with the variation of the estimated loads.

The variation in the epilimnion TP concentrations and the chlorophyll-a between the two studied periods (dry and wet) was statistically analyzed with the Kruskal-Wallis and Mann-Whitney tests. These non-parametric tests were suitable due to the unequal length of observations within each period. They were also performed to evaluate differences between surface TP concentrations and those measured in other depths. The results allowed to reinforce the representativeness of the epilimnion concentration for the water column at the sampling point. Statistical packages in Python programming were used for pairwise comparisons.

Additionally, a sensitivity analysis was carried out to identify the most influencing parameters in the modeling and support the understanding of the variability or the estimated loads. The reservoir inflow and volume were chosen to evaluate since they were explanatory variables of the proposed predictive models for the wet and dry periods, respectively. The other evaluated variables were the elapsed time between the TP measurements and the ratio of the final TP concentration by the initial concentration ($TP(t)/TP_0$). One variable was taken at a time to test a range of variation while the others were kept unchanged. As a preliminary result, these four variables were listed as the highest influencing ones. Then, considering the maximum mean error of the reference load of 31% (which will be further addressed in details), one parameter was tested at a time varying by $\pm 30\%$ as the others remained unchanged. The mean deviation in the estimated loads were discussed.

Correlation analysis

The TP load presents some well-known characteristics and strong correlations with parameters related to the catchment or the reservoir. Firstly, larger catchments have the potential to produce more TP load (Marques et al. 2019). Additionally, there is a relation between nonpoint sources P pollution with

flow conditions (Greene et al. 2011). Some particular correlations even between internal and external load were also reported in literature (Nürnberg et al. 2012). In contrast, the complex behavior of the internal load brings more undefined correlations with these parameters. Aiming to explore the existence of similar relationships in the studied area, a correlation analysis was carried out between TP load and catchment area, load of wet period and reservoir inflow, load of dry period and reservoir volume, and loads of the wet and dry periods. The goodness of fit was evaluated through the Pearson's correlation coefficient.

Results and discussion

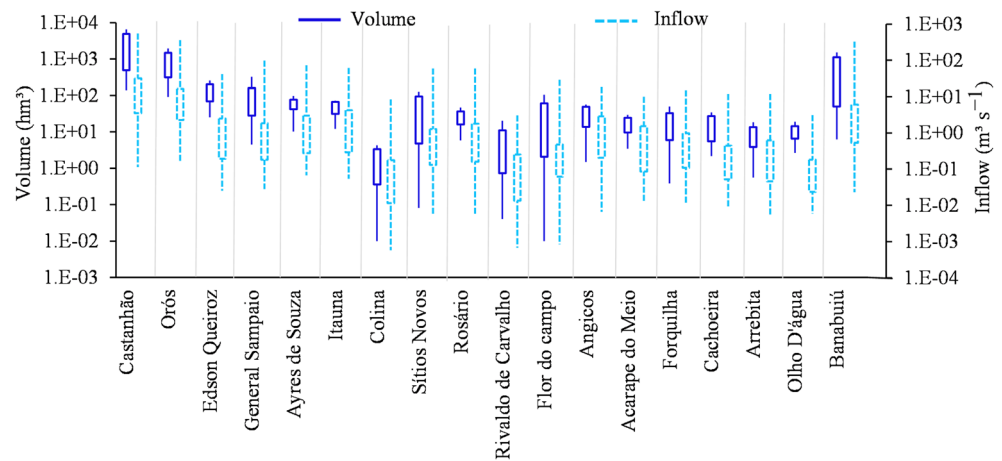
Catchment and reservoir hydrology

The variation of the volume and the inflow regime of each reservoir for the studied period are presented in Fig. 2. The interannual variability of the reservoirs' volume can be observed in the large range of variation of the boxes. The reservoirs Orós, Castanhão, and Banabuiú differed from the others with the highest stored volumes in the period. Their median volume was roughly 1363 hm^3 while the maximum median volume after them was 79.95 hm^3 for the Edson Queiroz. The reservoirs Colina, Flor do Campo, and Rivaldo de Carvalho achieved critical storage in the studied period with minimum volumes ranging from 0.01 to 0.04 hm^3 . These reservoirs are the smallest ones and become nearly empty on a yearly basis, which makes them "annual reservoirs." Contrastingly, the larger and more resilient ones (Orós and Castanhão) are considered "interannual reservoirs" (Lopes et al. 2014; Campos et al. 2016; Lacerda et al. 2018).

Regarding the mean inflow, the sum of the mean streamflow from the rivers and tributaries flowing to the reservoir, a great variation of flow regime was observed. The reservoir Olho D'água presented the lowest values, from 0.003 to $3.07 \text{ m}^3 \text{ s}^{-1}$, while the Castanhão catchment produced the highest ones, from 0.11 to $549.13 \text{ m}^3 \text{ s}^{-1}$. Additionally, some catchments could be grouped by similar characteristics in the period. The reservoirs Cachoeira, Arrebita, and Forquilha, with the smallest catchments and an average precipitation on record of 916 , 1063 , and 679 mm yr^{-1} , respectively, presented similar inflow patterns in the period, from 0.008 to $14.97 \text{ m}^3 \text{ s}^{-1}$ in average.

Similarly, the reservoirs Angicos and Acarape do Meio presented similar patterns, from 0.007 to $14.44 \text{ m}^3 \text{ s}^{-1}$ in average, with median inflows of 0.63 and $0.69 \text{ m}^3 \text{ s}^{-1}$ and catchment areas of 285.62 and 210.01 km^2 , respectively. In contrast, the catchment of the reservoirs Rosário, Rivaldo de Carvalho, Colina, and Flor do Campo, though, has shown a more anomalous behavior compared with the others. Rosário presented a small variability while the remaining presented

Fig. 2 Main hydrologic variables of each reservoir for the studied period



low values of inflow. It is noteworthy that the catchments of Flor do Campo and Colina share similar climatic characteristics due to their proximity (about 40 km between reservoirs). They had average precipitations of 577.10 mm yr⁻¹ and 615.40 mm yr⁻¹, respectively, which are very low and, as a consequence, contribute with low inflow rates.

Changing in precipitation levels throughout years is the main driver for interannual variability in reservoir volume and inflow in the State of Ceará (Broad et al. 2007), as a decline in the mean inflow is expected mostly during low precipitation periods (Zhang et al. 2015). Besides, the reservoirs have experienced a dramatic reduction on their volume due to the prolonged drought during the studied period (Lacerda et al. 2018, Wiegand et al. 2020). Mamede et al. (2018) also highlight the reservoirs' density in the watersheds of Ceará as a contributing characteristic to the inflow variabilities since the reduction of the contributing area to downstream and strategic reservoirs reduces the inflow consequently.

Characterization of the water column TP concentration

The variation of the TP concentration in the hypolimnion and epilimnion was evaluated for the reservoirs from measurements at the sampling points near the dams. The dataset collected encompasses the entire studied period. Fig. 3 summarizes this result for four reservoirs. They were selected because their depth ranged from the shallowest to the deepest reservoir. The vertical profile of the seasonal mean TP concentration for each depth in the studied period is presented along with the standard errors. In the wet period, the mean TP concentration in the water column, considering the measurements in all depths, varied from 37.39 to 533.86 µg L⁻¹, with a median of 67.87 µg L⁻¹. In the dry period, the ranges were from 27.73 to 227.35 µg L⁻¹ with a median of 61.93 µg L⁻¹. The statistical analysis was performed between the two datasets encompassing all measurements in the wet and dry

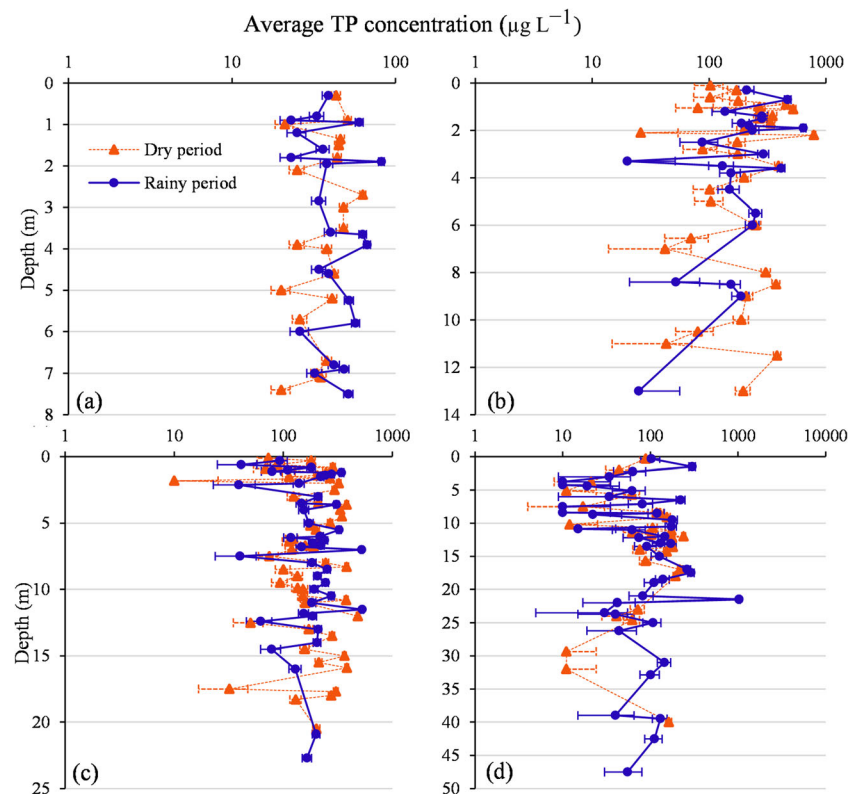
periods. The results indicated no significant *p* value to support differences in the average TP concentration in the water column between these periods (*p*>0.05) for seventeen reservoirs, except Colina, which is the shallowest reservoir. Shallow water bodies are more susceptible to wind-induced water column mixing which leads to increasing nutrient concentration driven by resuspension (Nürnberg et al. 2012).

Overall, it was observed that the mean concentration for the two seasons is very similar for more than 90% of the reservoirs. This was attributed to a trade-off between the hydrological and limnological processes occurring in the two seasons, following the dynamics described by Eq. (1). While in the wet period, the total load, reservoir volume, and flushing rate are expected to be higher; in the dry period, all these parameters are expected to be lower. On the other hand, while in the wet period, the retention time is expected to be lower and, consequently, the settling loss rate is higher, the contrary is expected to occur in the dry period (see Eqs. 2, 3, and 4).

Additionally, the Mann-Whitney and Kruskal-Wallis tests performed between the values in the upper surface (0.3 m deep) and the values in the other depths presented significant *p* values for 50% of the reservoirs (*p*<0.05). This suggests that for some reservoirs, there is a marked mixing behavior and similar TP concentration between upper and lower layers as shown in Fig. 3. It is important to highlight that the mixing state, mainly in polymictic lakes, might be variable among years (Nürnberg 2009). Specifically, in the Castanhão reservoir, previous studies indicate that TP concentration measurements present similar values between surface and bottom waters, but with a slight increase towards the bottom (Lacerda et al. 2018).

High tributary inputs of P and release from anoxic sediments might be sources of contribution to the vertical variation of phosphorus concentration in the water column (Nürnberg et al. 2013). P released from sediments has the potential to increase phosphorus concentration from processes such as diffusion and/or water column mixing and, especially under anoxic conditions, when it can also mix into the epilimnion

Fig. 3 TP concentration in the water column for the sampling point near the dam of the reservoir **a** Itaúna, **b** Sítios Novos, **c** Acarape do Meio and **d** Castanhão. Averages from 2008 to 2019 and standard errors (bars) are presented



(Nikolai and Dzialowski 2014). Particularly for the studied period, while a drought event was in course, stronger mixing conditions occurred. The reduction of volume during drought events and the consequent decrease in water depth might have led to breaking of the thermocline due to wind forcing and contributed to the mixing in the entire water column (Lacerda et al. 2018). Additionally, the effect of wind shear under relatively shallow water conditions potentially caused wind-induced resuspension of sediment and phosphorus, as already pointed out by Araújo et al. (2019) and Mesquita et al. (2020). It is important to highlight that the analysis in the present study was performed for the sampling points near the dams. Hence, spatial variabilities might pose differences for other regions of the reservoirs.

Impact of the drought period in the water quality and reservoir volume

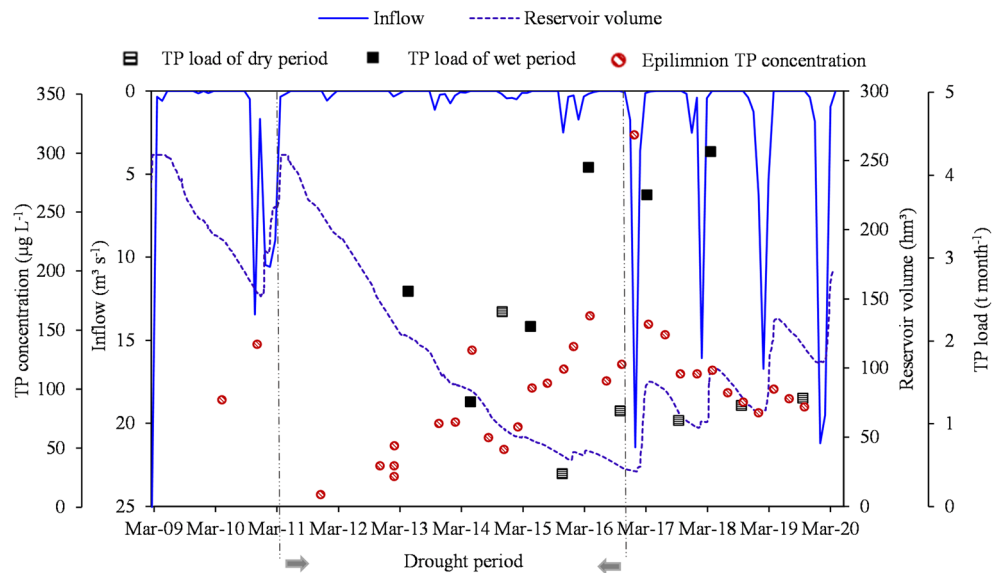
Fig. 4 presents the temporal distribution of volume, inflow, epilimnion TP concentration, and wet/dry period loads for the reservoir Edson Queiroz in the studied period. This reservoir was chosen since it presents typical characteristics of all studied reservoirs. The period of remarkable low inflows encompassing from 2011 to 2017 is similar to all other reservoirs along with the increase in epilimnion TP concentration. During this period, they all also presented a drastic volume reduction. For the reservoir Edson Queiroz, the remaining volume at the end of 2016 represented 17.6% of the initial

volume in 2011, a reduction from 152.5 to 26.9 hm^3 . The largest and strategic reservoirs Orós, Castanhão, and Banabuiú were those which caused more concerns about their volume reduction. At the end of 2016, they reached 14.3%, 5.1%, and 0.43% of their total volume, respectively.

The observed depth reduction during the dry season (considering the difference in water level between the two dates on which the TP measurements were performed) was 1.3 m on average, varying from 0.32 to 5.53 m. The reservoir that showed the highest level variation was Banabuiú (5.53 m between July and November 2014) and Castanhão (3.66 m between August and December 2015). In the dry period, the evaporation loss and the withdrawal for human consumption are mostly responsible for this water level variation. Additionally, drought events can intensify large variations in water levels, which consequently might cause changes in the physical, chemical, and biological characteristics of the waterbodies (Moss 2011).

From the wet period of 2017, the inflow pattern increased drastically presenting a peak of 21.46 $\text{m}^3 \text{s}^{-1}$ which was 18-fold higher than the average inflow of wet period since 2010. During the wet period of 2017, the highest TP concentration was also measured (314 $\mu\text{g L}^{-1}$). As already pointed out herein, in waterbodies with a high level of trophy, sediment resuspension by storm events favor nutrient resuspension and increase in nutrient concentration (Seitz et al. 2020). Additionally, higher loads were observed from the increase in inflow as annual external P loading is strongly related to storm events (Carpenter et al. 2014; Rattan et al. 2017).

Fig. 4 Time series of volume, inflow, epilimnion TP concentration, and wet/dry period loads for the reservoir Edson Queiroz



The TP concentration of the overlying water has showed a pattern of continuous increase from 2011 to 2017, from 34 $\mu\text{g L}^{-1}$ in February 2011 to 161 $\mu\text{g L}^{-1}$ in April 2016, while the reservoir volume decreased continuously, as the studied region faced the drought event (Wiegand et al. 2020). Cavalcante et al. (2018) analyzed two semiarid reservoirs during a drought period and observed the highest average TP concentration values during the periods with lower depth. Extended droughts, particularly, have an important role in water quality deterioration due to increasing concentrations of nutrients (Lacerda et al. 2018).

Fig. 4 also shows the mean-modeled TP load for each semester throughout the studied period. As already mentioned, the load during the dry period can be caused by both sediment release and/or resuspension (Moura et al. 2020a). Particularly in shallow lakes, internal loading can promote elevated TP values in the epilimnion (Horppila et al. 2017). During the drought period, the water level of the studied reservoirs decreased significantly while the TP concentration in the epilimnion increased continuously. Accordingly, higher TP loads were found. The average relation between the load of the wet period and the load of the dry one was about 43% in this period. This might suggest the influence of the low depth in this process. Cavalcante et al. (2018) also reported the highest observed average TP concentration during periods with low depth. Additionally, changes in lake size, depth, and climate potentially affect the level of the critical nutrient and can facilitate a regime shift in the ecosystem (Seitz et al. 2020).

The wet season, on the other hand, presented a load 2.75-fold higher, in average, than that of the dry season. This loading type is highly variable depending on the changes in discharge and is highest during storm events (Song et al. 2017). As observed in Fig. 4, once the inflow levels started to recover after the intense drought period, higher loads were obtained,

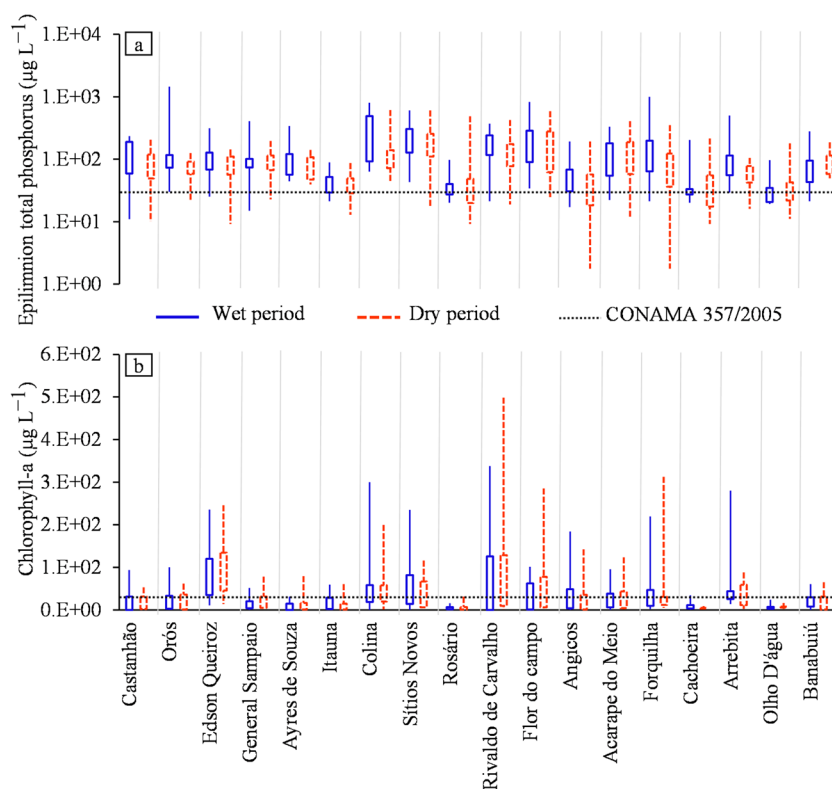
with peak values of about 4.33 t month^{-1} . Meanwhile, it is known that storm events in the dry period might contribute to over than 80% of the annual external P loading (Carpenter et al. 2014). Furthermore, the higher values of wet period load from 2017 highlight the importance of non-point sources of pollution for the waterbodies in semiarid regions. They are frequently the main external source of nutrients to reservoirs during the rainy season (Medeiros et al. 2015; Cavalcante et al. 2018).

Seasonal and interannual variation in epilimnion total phosphorus and chlorophyll-a concentration

The epilimnion TP concentration and chlorophyll-a concentration measured in the wet and the dry period of each reservoir are presented in Fig. 5. It is also shown the limiting concentration for class II according to national standards for lentic waterbodies (Brazil 2005). The waterbody classification considers to which purpose the water can be used for. Class I indicates the highest water quality level for noble uses, and class III is for consumption after enhanced treatment. All studied reservoirs are classified as class II with a limiting concentration of 30 $\mu\text{g L}^{-1}$ for TP and Chl-a.

The reservoirs remained eutrophic or hypereutrophic during great majority of the studied period (Ceará 2020a). The epilimnion TP concentrations for the dry period varied from 2 to 194 $\mu\text{g L}^{-1}$ in Angicos. This reservoir showed the highest percentage of good trophy state remaining over than 47.8% under mesotrophic classification. On the other hand, Colina which had the highest concentrations (44–599 $\mu\text{g L}^{-1}$) remained over than 76.9% of the study period in eutrophic or hypereutrophic classification. The high values of concentration also extend to the wet period. In comparison to the limit of 30 $\mu\text{g L}^{-1}$, there was a common disrespect to reach this

Fig. 5 Seasonal and interannual variability in **a** measured epilimnion TP and **b** Chlorophyll-a concentration



standard. As can be observed in Fig. 5, only 16.7% of the waterbodies have roughly 30% of their dataset under this limiting value.

The Kruskal-Wallis test performed between the concentrations in the wet and dry periods for each reservoir presented significant p values only for the reservoir Colina ($p < 0.05$) which presented the concentrations in the wet period higher than in the dry one. Colina is the shallower studied reservoir, then it is highly susceptible to drastic water level increase after rainy periods. These events may promote a strong mixing process and increase water column TP concentration combined with the contribution from the external load that comes with the inflow.

It is important to highlight, then, that the general analysis of the grouped dataset of epilimnion concentration in the wet and dry seasons has not presented statistically significant differences for almost all reservoirs. However, the analysis carried out in an annual timestep in each reservoir for paired concentrations comprised in the dry period showed that the great majority of the pairs presented a slightly higher TP concentration at the end of the dry period. This aspect might be a combined result of the volume reduction, which concentrates the nutrients, as well as an evidence of internal load (Nürnberg et al. 2012; Cavalcante et al. 2018).

Regarding the concentration of chlorophyll-a (Chl-a), its seasonal variability kept similarities with the TP concentration in the sense that it was not an observed marked differentiation between the periods. The statistical analysis revealed no

significant p value between the Chl-a concentration for the two periods for any reservoir. Indeed, the variation in the trophic state of the studied reservoirs was very narrow, and they remained eutrophic or hypereutrophic most part of the study period (Ceará 2020a). The median concentrations ranged from 3.56 to 80.98 $\mu\text{g L}^{-1}$ for the wet period and from 2.24 to 86.18 $\mu\text{g L}^{-1}$ for the dry period. The maximum values for both periods were observed in Rivaldo de Carvalho (337.63 $\mu\text{g L}^{-1}$ in the wet period and 501.85 $\mu\text{g L}^{-1}$ in the dry period). The higher values observed in this reservoir occurred in 2016–2017 when it remained with an average volume of about 1% of its capacity. As for the accordance with the limiting concentration, the Chl-a measurements followed the national regulation more often than what was observed for TP concentration.

The behavior of Chl-a may be better comprehended in light of the behavior of the epilimnion TP concentration, since their strong correlation is widely recognized. Classical studies have observed P (total and organic forms) as a good predictor for Chl-a concentration (Dillon and Rigler 1974). In Brazilian reservoirs, these relationships were also verified (Carneiro et al. 2014; Rocha et al. 2019) as well as in other regions world-wide, even by non-linear models (Filstrup et al. 2014). In opposite with classical reports, recent studies found that P remains as the limiting nutrient to the ecosystem productivity regardless of the nitrogen/phosphorus ratio (Kolzau et al. 2014). Then, as P concentration remained relatively similar among periods, so did the Chl-a concentration.

Furthermore, as further addressed, the variability observed in these water quality surrogates (TP and Chl-a) may be also linked with the TP loading pattern, which meant high variability in TP load but similar production among periods. In fact, long-term TP loading plays an important role on algal biomass (Tang et al. 2019).

Data uncertainties regarding sample collection and laboratory preservation or analysis may occur and influence the results (Harmel et al. 2006). However, the data accuracy was evaluated by an outlier analysis and by the order of magnitude of the reported TP concentrations in comparison with values reported in the literature. There was only one measurement over 4000 $\mu\text{g L}^{-1}$ which was excluded as a possible sampling error. Peak values (1500–4000 $\mu\text{g L}^{-1}$) represented less than 0.2% of the dataset and occurred mainly in 2016, during the lowest water depth, or in 2009–2010, after the strongest rainy season of the study period. Overall, the measured TP concentrations of the study sites were within reported ranges in the literature for eutrophic ecosystems (10–3300 $\mu\text{g L}^{-1}$) (Rattan et al. 2017; Han et al. 2018; Li et al. 2020). For the chlorophyll-a data, only four values (0.5% of the dataset) were exceptionally high and then, removed.

Phosphorus load estimates for the wet and dry periods

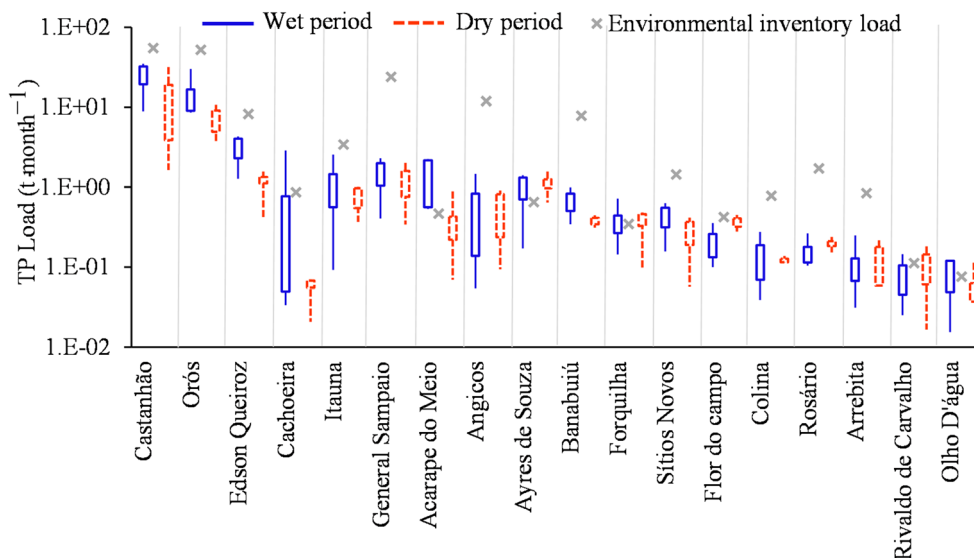
The modeled TP load for the wet and the dry periods along with the reference TP load value estimated by COGERH is shown in Fig. 6. The load of reference was used to strengthen the modeled estimations obtained in the present study.

With regard to the loads estimated during the wet season, the values varied from the minimum of 0.015 t month⁻¹ in Olho D’água to 34.76 t month⁻¹ in Castanhão, with a median value of 2.81 t month⁻¹. Some exceptionally high modeled TP load was obtained, and their probable causes will be further

addressed as the results of a sensitivity analysis of the model. High values were obtained for larger catchments as they have the potential to produce more TP load mostly from nonpoint sources (Marques et al. 2019). Specifically, for the Castanhão catchment, several studies were carried out. The agriculture contribution in this catchment was estimated around 116 t yr⁻¹, in average 9.67 t month⁻¹ (Paula Filho et al. 2019). Lacerda et al. (2018) estimated 212 t as a flux of TP load for the Castanhão reservoir for the 6-month of the wet period from measured TP concentration and inflow (about 35.33 t month⁻¹), which was very similar to the highest value obtained in this study (34.76 t month⁻¹). In some highly eutrophic systems, such as the studied reservoirs, large portion of the load from the wet period possibly settles and becomes recycled within the same year which might impact the internal load estimation by resembling sediment-released P (Nürnberg 2009). Additionally, due to the settling process, only a certain percentage of external load can effectively contribute to lake water TP (Nürnberg et al. 2013).

It can also be seen in Fig. 6 that the estimated values were slightly under the reference load for the catchments, and more significantly underestimated for 33% of them. For the remaining, the reference value was very close to the value reported by COGERH or in the range of the modeled TP load. The correlation between the mean modeled TP load and the reference load for the reservoirs resulted in a $R^2 = 0.82$ with a bias varying from 2.9 to 96.2% with an average of 65.9%. The underestimation of the TP load in some catchments may be due to the temporally spaced sampling data, only three or four times per year, which tend to underrepresent peak storm or high-flow events. This way, the likely intense phosphorus dynamics in the waterbody that happen at the moment and in a short period after it may not be accounted (Johnes 2007; Bowes et al. 2009). Moreover, the reference load was estimated in a period with higher inflow levels (from 2008 to 2011

Fig. 6 Seasonal and interannual variations in the modeled TP loads for the wet and dry periods



depending on the reservoir) than the average of the studied period, then it has possibly accounted more external load.

Concerning to the load of dry period, the estimates varied from the minimum of $0.016 \text{ t month}^{-1}$ in Rivaldo de Carvalho to $31.19 \text{ t month}^{-1}$ in Castanhão, with a mean value of $1.09 \text{ t month}^{-1}$. The modeling process resulted in 14% of negative estimates in average with a maximum of 48% for the Acarape do Meio reservoir. Positive values indicate that internal P loading occurs in the sediment whereas negative values imply P retention (Song et al. 2017). As can be observed in Fig. 6, the load estimated during the dry period had similar order as those of the wet period for the majority of the reservoirs. Lepori and Roberts (2017) suggest that shallow lakes are more affected by internal loading than deep ones, once deep lakes have a larger volume of water to dilute the P released from the sediments. The studied reservoirs have faced a drastic volume reduction, what may have corroborated to the high values of load produced during the dry season even in once deep reservoirs. Additionally, due to the climatic conditions of the studied area and the complete dryness of the rivers in the dry season, no inflow arrives in this period. Then, significant external inputs of nutrients are not expected (Barbosa et al. 2012). So, internal loading was potentially the main source of P load to the reservoirs during dry periods (Nürnberg 2009).

Significant differences between the loads produced in the two periods were statistically relevant only for Acarape do Meio and Edson Queiroz reservoirs (p value < 0.05). They presented wet period loads about three- and fourfold higher than the dry period load, respectively. The environmental inventory of these reservoirs reports that the highest annual P input comes from soil and agriculture for Edson Queiroz and Acarape do Meio respectively. Additionally, Edson Queiroz has the fourth largest catchment area, and the Acarape do Meio has the second highest rainfall index, which enhances external load dominance. For the remaining reservoirs, the statistical test which analyzes the median has not found significant differences, in spite of some reservoirs presenting peak values for the wet period load. The inter seasonal increasing pattern observed in the epilimnion TP concentration in the sampling points corroborates these results. From the beginning to the end of each period, the increase in the values may suggest an input of TP load. As observed in Fig. 5a, the seasonal behavior of epilimnion TP concentrations was similar, such as the one of the loads. Furthermore, beyond the contribution of the volume reduction to increase concentration, as this reduction is less remarkable annually than the long-term interannual volume variation, the occurrence of internal P loading in the dry period is an additional source potentially counterbalancing the external P inputs during the wet period.

The observed among-catchment variation of TP flux for the load of wet period can be largely explained by differentiated

net anthropogenic P input as well as seasonal variations of water discharge in the rivers (Han et al. 2018; Hu et al. 2020). For the load of dry period, it may depend on climatic conditions and the level of oxygenation in the water-sediment interface (Cavalcante et al. 2018). Additionally, the existence of aquaculture is another relevant aspect, as it releases nutrients directly to the water column (Santos et al. 2016). This contributes to the water quality deterioration (Oliveira et al. 2015). In the Castanhão reservoir, the aquaculture may contribute to roughly 163 t yr^{-1} , in average $13.58 \text{ t month}^{-1}$ (Lacerda et al. 2018). With regard to the among-season variations, a trade-off between the P mechanisms, notably the physical processes, might contribute to similar estimates. During the wet season, the wind effect is weakened in comparison to the dry season, which might impact wind-induced resuspension. However, the external transport is markedly impactful during the wet period, once there has been no or little outflow/overflow during the dry season. With respect to other mechanisms mainly occurring in the water-sediment interface (such as diffusion, adsorption, and desorption), they may be better discussed when gross estimates are obtained, while in this study only net estimates through mass balance were performed.

Following Vollenweider (1968) and Chapra (2008), areal phosphorus loads were obtained, and the rates were expressed in terms of total P. Table 2 presents the average values estimated for each reservoir. The areal loads ranged from 0.07 to $1.04 \text{ gP m}^2 \text{ month}^{-1}$ for the wet season and from 0.05 to $0.65 \text{ gP m}^2 \text{ month}^{-1}$ for the dry season. For the dry period, the literature reports rates ranging between 0.11 and $0.30 \text{ gP m}^2 \text{ month}^{-1}$ with higher rates more common in eutrophic water bodies (Nürnberg et al. 2012; Nürnberg et al. 2013; Qin et al. 2016). The annual averages varied from 0.66 to $7.29 \text{ gP m}^2 \text{ yr}^{-1}$, which is consistent with the ones reported in the literature (0.15 – $7.06 \text{ gP m}^2 \text{ yr}^{-1}$) (Ahlgren et al. 1988; Nürnberg 1984; Kohler et al. 2005; Nürnberg et al. 2012).

Because of the dense reservoir network of the Brazilian semiarid, the mineral sedimentation (reservoir silting) is only about 20% of the rates observed in other reservoirs globally, as reported by Lima Neto et al. (2011). However, in the reservoirs studied in this work, the net sedimentation rate of total phosphorus ranged from about 60 to 90% of the input load, contrasting with an average of about 40% obtained for temperate lakes and reservoirs (Hejzlar et al. 2006). This higher net sedimentation rate of TP is attributed to the higher water temperature of the Brazilian semiarid reservoirs, which leads to a combined effect of increased P consumption by algae and increased physical sedimentation due to reduced water viscosity, corroborating the results of Toné and Lima Neto (2019). The above results indicate that P retention in the high-density reservoir network is potentially counterbalanced by the higher net sedimentation rates due to higher water temperatures, possibly resulting in similar areal P loads (up to about 7 gP m^2

Table 2 Mean areal phosphorus load for the wet and dry seasons and total annual load

Reservatório	Areal TP load (gP m ² month ⁻¹)		Areal TP load (gP m ² yr ⁻¹)
	Dry period	Wet period	
Olho D'água	0.05	0.07	0.66
Rosário	0.05	0.06	0.71
Itauna	0.07	0.08	0.87
Angicos	0.08	0.09	1.01
Arrebita	0.06	0.15	1.28
Cachoeira	0.09	0.22	1.91
Flor do campo	0.26	0.08	2.04
Forquilha	0.15	0.19	2.05
Rivaldo de Carvalho	0.22	0.13	2.16
Colina	0.10	0.30	2.48
Orós	0.13	0.28	2.56
Ayres de Souza	0.16	0.26	2.58
Banabuiú	0.11	0.32	2.86
Edson Queiroz	0.17	0.44	3.54
General Sampaio	0.23	0.49	3.97
Castanhão	0.27	0.54	4.60
Sítios Novos	0.51	0.32	4.98
Acarape do Meio	0.41	0.71	7.29
Statistics			
Minimum	0.05	0.06	0.66
25th	0.08	0.10	1.43
50th	0.14	0.24	2.32
Mean	0.17	0.26	2.63
75th	0.23	0.32	3.37
Maximum	0.51	0.71	7.29

yr⁻¹), as reported by Ahlgren et al. (1988), Kohler et al. (2005) and Nürnberg et al. (1984, 2012).

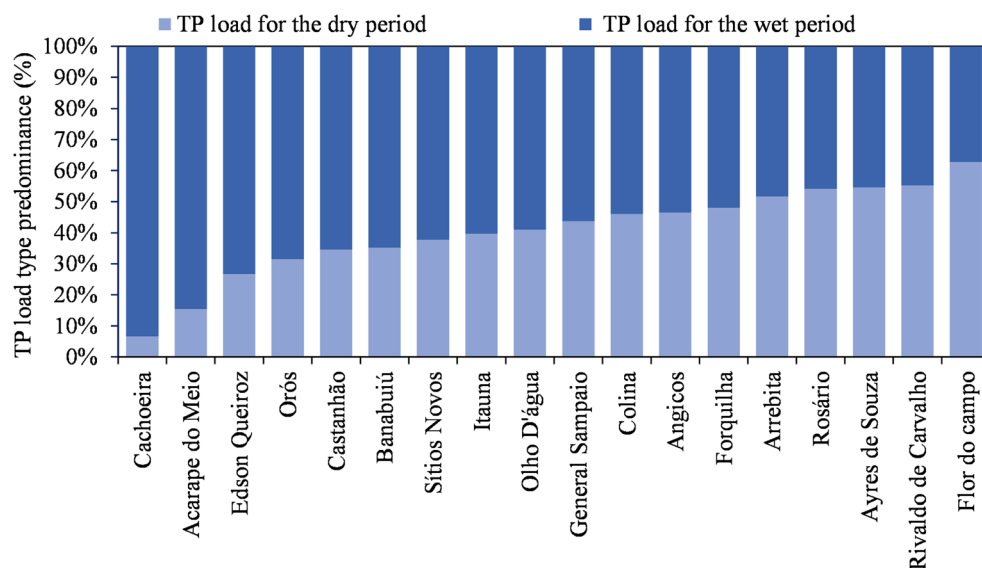
Load of dry season vs. load of wet season over the annual P budget

Fig. 7 shows the predominance by type of TP load for each reservoir. This estimate represents the average of the estimated values per period in relation to the annual load. The predominance of the dry period load varied from 6.56% in Cachoeira to 62.74% in Flor do Campo. For the reservoir Acarape do Meio, the second with the lowest dominance of dry period load, several studies in its catchment identified the intensity of external input mainly from point sources. Open-air dumps, illegal slaughterhouses, and four STW from which three discharge their effluents directly into the main rivers were identified in the catchment of Acarape do Meio (Lima et al. 2018). For the Orós and Castanhão reservoirs, in spite of the intense fish farming practice, they have larger and rural catchments (> 24000 km²) that concentrate the most relevant irrigated croplands of the state. Consequently, there is a high amount of

external TP production from nonpoint sources (CEARÁ 2020b). Similar analyses were applied for the for the Banabuiú reservoir.

A growing predominance of dry period load is observed in Fig. 7. From Arrebita reservoir, it surpasses 50%. The combination of the volume reduction with a wind-induced complete mixing condition might turn the reservoirs close to shallow polymictic ones, and recent literature provides evidence that polymictic lakes are more prone to have high internal P loading rates (North et al. 2015; Orihel et al. 2015; Cavalcante et al. 2018). In the lake nutrient budget, sediment P might have an increasing predominance (Doan et al. 2018). Thus, representing the load produced during the dry season as a percentage of the total annual load is a way to compare it with the load from the wet season and understand its importance (Nürnberg 2009). Song et al. (2017) highlights that in P-enriched agricultural areas, internal P loading can be as high as external one. The existence of high internal load production implies that the achievement of a stable mesotrophic condition will not occur until the substantial reduction of these loadings (Lepori and Roberts 2017). Moreover, it delays the decline of

Fig. 7 Assessment of the representativeness of the loads produced in the wet and dry seasons in the annual TP load



nutrient concentration in the water column as expected once there is a reduction of external load. Meanwhile, it may take a very long time to deplete the internal loading, especially in reservoirs with a long history of pollution (Schindler 2006). It is expected that, in general, changes of the released P depend on the mixing regime of the lake, trophic state, and chemistry (Nürnberg 2009). Additionally, high amount of phytoplankton might be related with the amounts of released P (Kowalczevska-Madura et al. 2019). An assessment of the internal loading percentage over the annual P load budget reported in the literature revealed a range from 2 to 89% (Nürnberg et al. 2012; Nürnberg et al. 2013; Loh et al. 2013; Nikolai and Dzialowski 2014; Matisoff et al. 2016; Lepori and Roberts 2017; Song et al. 2017; Kowalczevska-Madura et al. 2019), which highlights that the internal TP load can be as high as the external load.

Predictive models for TP load input

Simple predictive models were proposed as an attempt to assess the most correlated characteristics with the TP load. The correlations were developed between the TP load of dry period and volume, TP load of wet period and inflow, TP load of dry period and TP load of wet period, and total TP load and catchment area. Fig. 8 presents the models as well as the coefficient of determination for each one. The models were adjusted with mean values to reduce the bias, once the fitting with the entire dataset including the modeled values of all reservoirs presented a large variability. A satisfactory R^2 was obtained through a power-low curve adjustment. The residual analysis, in order to reinforce the quality of the models, was performed graphically.

Fig. 8 a presents a positive correlation between the TP load of dry period and the reservoir volume ($R^2 = 0.84$). A possible explanation relies on the relation between the reservoir volume and

the water-sediment interfacial area. A larger volume enlarges this interface and P production by release under appropriate conditions. Moreover, several aspects may be linked to this result. Larger reservoirs also have larger catchments in the study area. The reservoirs with this characteristic receive significant contributions of external load, and it can be seen in Fig. 8c that greater load in the wet period implies greater load in the dry period, possibly as a result of a long-term accumulation process.

The positive correlation between the TP load of wet period and the inflow ($R^2 = 0.94$) is largely known (Fig. 8b). This type of load is adequately explained by seasonal variations of water discharge in the rivers (Han et al. 2018), as stream discharge is a fundamental explanatory variable with a positive influence on external TP load (Rattan et al. 2017). Hydrologic events, such as peak storms, mainly in watersheds dominated by non-point sources, significantly contribute to external TP load (Jeznach et al. 2017). Its rates during peak flow events can be approximately five times higher than under normal conditions (North et al. 2015).

As shown in Fig. 8c, the dry and wet period loads were directly correlated ($R^2 = 0.98$). The higher the TP inputs during the wet period, the higher those in the dry one. This positive correlation indicates that an abatement of external P sources implies a decrease in the internal load. This also highlights the strong influence of the load produced during the wet period with that produced during the dry period. According to Nürnberg (2009), the wet period load is more susceptible to settle and be recycled within the same year in highly eutrophic systems. As the studied reservoirs remained highly eutrophic during the studied period, this aspect strengthens the obtained correlation. In contrast, an inverse correlation between these variables was already found (Nürnberg et al. 2012).

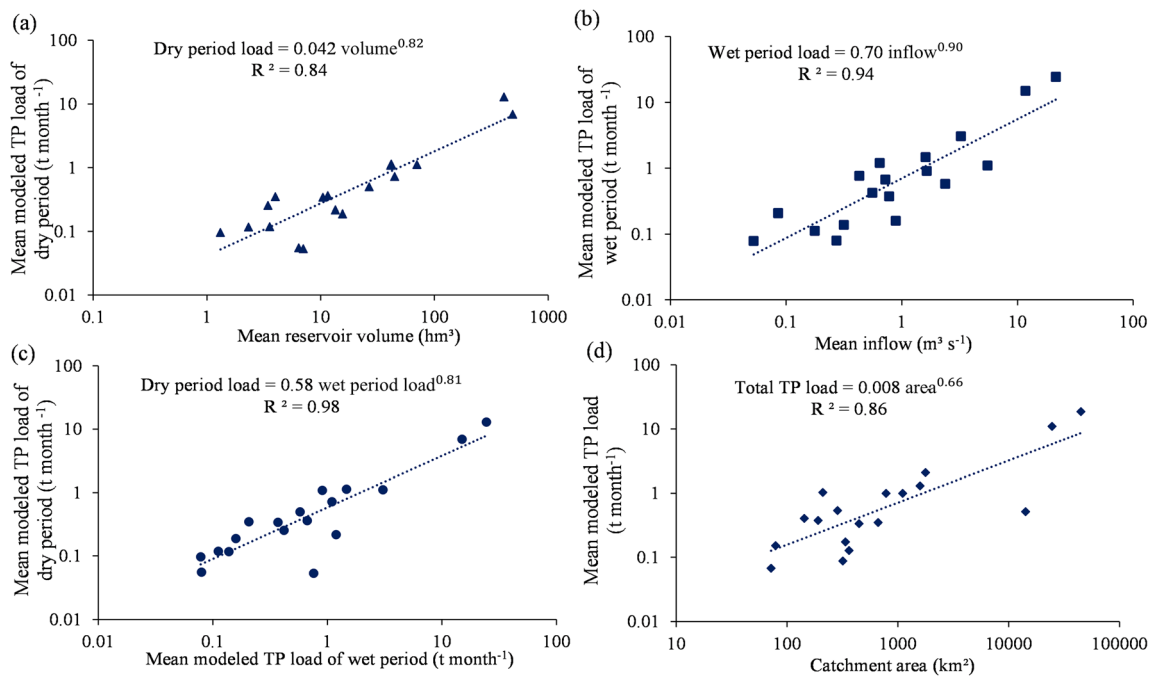


Fig. 8 Proposed models for the **a** TP load of dry period as function of the volume, **b** TP load of wet period as function of the inflow, **c** TP load of dry period as function of the TP load of wet period, and **d** Total TP load as function of the catchment area

Finally, the catchment area was shown as an important predictor of the total TP load entering a waterbody ($R^2 = 0.86$), as depicted in Fig. 8d. It is commonly expected and observed that larger catchments might produce more TP load, especially if there is an intensive agriculture exploitation on the lands (Marques et al. 2019). Additionally to agriculture, soil erodibility also plays an important role in the mobilization of pollutants (Li et al. 2020). Poorly drained soils can transfer the most diffuse P load (Greene et al. 2011), particularly in semiarid watersheds (Paula Filho et al. 2019).

The ultimate analysis performed was the estimation of the TP load through a concentration-flow relationship particularly for the Castanhão reservoir. Thus, a comparison between the load obtained through calibration of the Eq. (1) with the one obtained through the concentration-flow relationship was performed. Fig. 9 presents the comparison of the modeled loads encompassing the period from 2013 to 2019. The estimated loads varied from 0.002 to 51.03 $t\ month^{-1}$ for the concentration-flow relationship modeling approach and from 0.24 to 34.99 $t\ month^{-1}$ for the mass balance approach. The NSE between the models was 0.67, which turned the quality of the adjustment satisfactory (Moriassi et al. 2007).

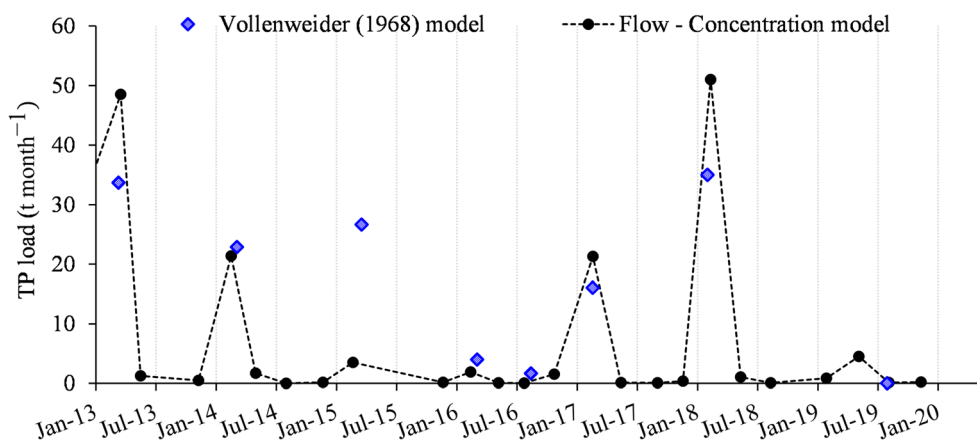
The most distant result between the models was obtained for the estimation in 2015. In the dry period of this year, the reservoir presented a very low volume and high measured epilimnion TP concentrations. This implied a higher load estimate by the model of Vollenweider. On the other hand, the low flow rates measured in the river resulted in lower load estimates by the flow-concentration model. Combined, these factors enlarged the difference between the models. However,

considering the overall comparison of the results, the classic predictive model of Vollenweider is properly capable to perform a good estimation for the load of the wet period, once this load type has formed the basis of development for this model (Schauer and Chorus 2009).

Model implications, uncertainty, and sensitivity analysis

The results of the sensitivity analysis showed that the elapsed time (t) and the ratio $TP(t)/TP_0$ had an important influence regardless of the loading type. Short t between measurements resulted in higher estimated loads. However, the impact of t was more pronounced combined with the ratio $TP(t)/TP_0$. As expected, if considerable average TP increase is observed, especially if it occurs in a short interval, peak load events might have induced this increase. Dropping t by half resulted in a mean deviation from the original estimate of 20% when $TP(t)/TP_0 < 2$ and 50% when $TP(t)/TP_0 > 4$. Then, paired concentrations with elapsed time less than 1 month were not considered, although this situation was rarely observed in the dataset. Considering only the effect of the ratio, for $TP(t)/TP_0 = 1.5$, the mean deviation accounting all estimated loads reached about 40%. As for the impact of the inflow, the tested range of variation (30%) resulted in an average deviation of the wet period load of about 10%, considering all reservoirs' estimates together. However, as it was observed and as further detailed, for some reservoirs marked interannual differences in the inflow, that far surpassed this percentual, caused large differences in the estimates between years. For the volume

Fig. 9 Comparison of the total TP load input to the Castanhão reservoir by using two different approaches



influence, a deviation of $\pm 30\%$ resulted in a mean deviation of the same magnitude for the dry period load. For the wet period load, the volume variation influence was smaller (about 20% in average).

Knowing the sensitive parameters of the modeling and their impact on the estimates turns possible to evaluate the variability of the modeled loads. The coefficient of variation (CV) ranged from 0.40 to 2.08 with mean of 0.99 for the load of wet period and from 0.09 to 2.03 with mean of 0.70 for the load of dry period. Although these values appear to be high, they were only a few estimates influenced by uncommon conditions which elevated the median values. For the wet period load, the CV of 2.08 was obtained for the reservoir Sítios Novos accounting the load estimated for 2011, the highest inflow among the years, whose measurements presented a $TP(t)/TP_0$ ratio of 1.9. The reservoir Cachoeira presented the second highest CV of 2.07. Similarly, it was obtained for the estimate of 2014, which had the highest inflow of all years and $TP(t)/TP_0$ ratio of 4. Disregarding these peak values would drop the average CV to 0.77 and the maximum to 1.0. For external loads, the literature reported CV ranges of 0.05–0.71 (Kulasova et al. 2012; Chapra and Dolan 2012). Then, the average CV of this study is very close to these reports. The high interannual climatic variability typical of semiarid conditions may be largely responsible for this slightly elevated average. The ratio between the inflow of the rainiest year with the driest one for the studied period resulted in a median value of 6.2. In fact, due to the drought period, the inflow during the period 2008–2011 was markedly superior than during 2013–2016.

For the estimated load of the dry period, the maximum CV of 2.03 was obtained for the reservoir Acapare do Meio as a result of a peak estimate in 2009. In this year, the $TP(t)/TP_0$ was 6.4 (from 62 to 399 $\mu\text{g L}^{-1}$). The reservoirs Sítios Novos and Castanhão also presented peak estimates for the years 2008 and 2010, respectively. The first one was mainly influenced by the high $TP(t)/TP_0$ ratio of 7.2. The second was majorly due to the short elapsed time between the TP measurements. By disregarding these peak estimates, the CV range would change from 0.09 to 1.24, with average of 0.58. For internal load, reported CV ranged from 0.33 to

0.83 (Spears et al. 2012; Nürnberg 2009, 2012, 2019; Horpilla et al. 2017). Thus, the values obtained here are in accordance with the literature. Moreover, for some higher variations still remaining, the interannual variation in the volume reduction and the rapid deterioration under drought conditions strongly influence the estimates of the dry season. Furthermore, for the years with strong rainy seasons, the possible water mixing during elevated inflow events and rapidly volume increase during the wet season resulted in following dry periods with higher water column TP concentration. The water level variation and inflow turn the internal TP load estimation particularly challenging in complex managed reservoirs (North et al. 2015), especially in the study sites under a tropical semiarid climate.

Regarding the reference TP load, previous studies that have already applied the ECM reported a maximum mean error of 31%, as already mentioned. Then, for the catchments whose reference load was underestimated, this range of mean error in computing the reference TP load might be taken into consideration. Besides, for the most distant results, variations in the input data to the modeled load may have had greater influence on this difference. For seasonal and spatial data, the monitoring frequency, quality, and quantity significantly contribute to the accuracy of the load assessment (Nürnberg 2009). Error exclusively due to variability of P concentrations is at least 20% on average for lake samples (Nürnberg et al. 2012).

Existing limitations are mainly related with TP load estimation, since the developed models rely on the accuracy of the extensive field study carried out by COGERH. It has to be highlighted, though, that the data limitation on the studied area largely reduces the range of possible useful alternatives to perform a data comparison and validation. Additionally, sampling interval, analysis, and data quality manipulation inaccuracies in reservoirs' data can have an impact in the load estimation process and in the modeled outputs. Moreover, in the data frequency of roughly 12 years of sampling in reservoirs, high-flow events remained under-represented. Only 5 years in the studied period presented precipitation indexes roughly above the average in all catchments. Thus, low to medium flow were more frequent in the study dataset which may

have reduced the possible amount of TP load produced in the wet season.

Finally, addressing the main implications of the method developed in this research, mainly regarding the issue of controlling phosphorus production, the contributions can be evaluated at the individual level per reservoir or encompassing the integrated network of reservoirs. The modeling of scenarios to assess the impact of mitigation measures regarding external inputs, such as the expansion of sanitation coverage on the catchment or the regulation and inspection on the application of phosphorus-enriched fertilizers in agriculture, may be a tool to assist reservoir management. Additionally, regardless of the loading type, the required load reduction may be evaluated so that the TP concentration of upper layers reach the limits established by national water quality standards. Lastly, a target phosphorus concentration may be defined during the occurrence of extreme hydrological scenarios, such as drastic reduction in volume and inflow, to determine the associated maximum phosphorus load. This assessment would assist an efficient integrated management of the reservoirs and their prioritization by type of water uses.

Conclusions

The analysis of seasonal epilimnion TP concentrations between the wet and dry periods resulted in insignificant differences ($p > 0.05$) for more than 90% of the reservoirs, which was attributed to a trade-off between the hydrological/limnological processes occurring in the two seasons. However, a slightly higher overlying concentration at the end of the dry period was observed. The statistical tests performed between the concentrations in the upper surface (0.3 m depth) and in the other depths also revealed no significant p values for 50% of the reservoirs ($p > 0.05$). This suggests that many reservoirs tended to present a well-mixed behavior. Then, a complete-mix mass balance model was applied. For the dry period, the modeling process resulted in only 14% of negative TP load estimates on average. While negative values imply P retention, positive ones indicate that internal P loading occurred. The results also indicated that a high amount of load from the dry period contributed to the annual budget, with estimates varying from 0.016 to 31.19 t month⁻¹. The predominance of the dry period load over the annual TP input varied from 6.56 to 62.74%. This suggests that the eutrophic state and shallow water condition of the studied reservoirs have possibly contributed to the settling and recycling of the external load within the same year. The areal TP load estimates ranged from 0.66 to 7.29 gP m² yr⁻¹, consistently with the literature (0.146–7.06 gP m² yr⁻¹). This implies that TP retention in the dense reservoir network is potentially counterbalanced by the higher net sedimentation rates due to higher water temperatures.

Power-law curves were adjusted between internal TP load and volume, internal and external TP loads, external load and inflow, and total TP load and catchment area, resulting in satisfactory R^2 of 0.84, 0.98, 0.94, and 0.86, respectively. Despite the uncertainties involved in the estimations, the findings from this work are novel as the quantification of external and internal P loads was approximated by the estimation of the loads produced during the wet and dry periods, respectively. Additionally, their relative importance to the annual input load was evaluated, and predictive correlations were proposed. This study not only advanced the knowledge of P dynamics in tropical semiarid reservoirs, but also provided evidences of important internal loadings to these systems. Furthermore, the methodology applied in the study might be directly applicable to water bodies with similar characteristics in other dryland regions.

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Author contribution MJDR collected, analyzed and interpreted the data, and wrote the manuscript. IELN supervised the research, analyzed and interpreted the data, and revised the manuscript. All authors read and approved the final manuscript.

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Data availability The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate Not applicable

Consent for publication Not applicable
Competing interests
The authors declare no competing interests.

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