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Scientific Paper

Impacts of water quality on water availability of reservoirs in the state of Ceará

Impactos da qualidade de água na disponibilidade hídrica de reservatórios do estado do Ceará

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ABSTRACT

This study aims to analyze the impacts of water quality on the water availability of reservoirs using the total phosphorus (TP) concentration as an indicator. Three reservoirs in the State of Ceará were investigated for this purpose: Acarape do Meio (29.6 hm^3); Aracoiaba (162 hm^3); and Pentecoste (395.6 hm^3). For estimating the TP load yielded in the studied catchments, equations that correlate census data on animal, agricultural and human production with TP gross production were applied. The TP balance in the three reservoirs was carried out based on the Chapra equation for complete mixing, considering periods with different hydrological regimes: wetter period (2004 to 2010); and period with prolonged drought (2011 to 2020), indicating a decay relationship of TP concentrations for larger stored volumes. This study proposed the introduction of the PIR (Phosphorus Input Ratio) concept, which refers to the ratio between the TP input load into the reservoir and the gross TP load yielded in the catchment. Considering that the hydrological regime can influence the TP transport conditions, a correlation between PIRs and runoff coefficients was established, presenting a good adjustment. The effects of including water quality restrictions regarding TP content on water availability at the reservoirs were also addressed. TP concentrations at the reservoirs can negatively impact water availability subject to quality constraints. Therefore, the adoption of techniques to reduce the production and export of TP from the study areas is extremely important for making water available within the quality standards required.

Keywords: reservoirs; total phosphorus; water yield.

RESUMO

Este estudo tem como objetivo analisar os impactos da qualidade da água na disponibilidade hídrica dos reservatórios utilizando a concentração de fósforo total (TP) como indicador. Para esse fim, investigaram-se três reservatórios no estado do Ceará: Acarape do Meio (29,6 hm^3), Aracoiaba (162 hm^3) e Pentecoste (395,6 hm^3). Para estimar a carga de TP produzida nas bacias hidrográficas estudadas, aplicaram-se equações que correlacionam os dados censitários das produções animal, agrícola e humana com a produção bruta de TP. O balanço de TP nos três reservatórios foi realizado com base na equação de Chapra para mistura completa, considerando-se períodos com diferentes regimes hidrológicos: período mais úmido (2004 a 2010) e período com seca prolongada (2011 a 2020), indicando uma relação de decaimento das concentrações de TP para maiores volumes armazenados. Este estudo propôs a introdução do conceito PIR (razão de aporte de fósforo), que se refere à razão entre a carga de entrada de TP no reservatório e a carga bruta de TP produzida na bacia hidrográfica. Considerando-se que o regime hidrológico pode influenciar as condições de transporte do TP, estabeleceu-se correlação entre os PIRs e os coeficientes de escoamento superficial, apresentando bom ajuste. Também foram abordados os efeitos da inclusão de restrições de qualidade da água em relação ao teor de TP na disponibilidade de água nos reservatórios. As concentrações de TP nos reservatórios podem impactar negativamente a disponibilidade hídrica, sujeita a restrições de qualidade. Portanto, a adoção de técnicas para reduzir a produção e a exportação de TP das áreas de estudo é de extrema importância para disponibilizar água dentro dos padrões de qualidade exigidos.

Palavras-chave: reservatórios; fósforo total; disponibilidade hídrica.

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INTRODUCTION

In the State of Ceará, precipitation is concentrated in a few months of the year, with high intensity and short duration, increasing surface runoff generation, especially considering that 74% of the state's soil is on the crystalline basement. Geomorphological and climatic conditions led to the construction of a dense network of reservoirs in the state, promoting an increase in water retention time and the accumulation of sediments and nutrients (WIEGAND *et al.*, 2021; LIMA NETO *et al.*, 2011). This enrichment of nutrients has resulted in the acceleration of eutrophication of water bodies in the state with the emergence of macrophytes, increased concentrations of chlorophyll-a and phosphorus (P) (ROCHA; LIMA NETO, 2021).

The modeling of physical, chemical and biological phenomena, including the reliable representation of these events and processes at different scales close to reality in a simplified and practical way, enables the assessment of different interactions in complex systems such as rivers, forests, cities and climate (FABIAN *et al.*, 2023; LIMA NETO *et al.*, 2022). Modeling practices in aquatic environments have contributed to support the planning and management of space and use of natural resources in different hydrological models and scales through scenario simulation (RAULINO; SILVEIRA; LIMA NETO, 2021).

Modeling TP in reservoirs makes it possible to predict flows based on rainfall data and contributes to indirect applications, used as boundary conditions, such as in the quantification of nutrients arising from changes in land use in the river basin (FREIRE; COSTA; LIMA NETO, 2021). Wiegand *et al.* (2021), for example, estimated the polluting capacity of semiarid reservoir catchments considering the generation of nutrient load by point and non-point (diffuse) sources based on modeling.

Modeling TP concentration in reservoir is a useful tool for effective water management (ROCHA; LIMA NETO, 2021), allowing a better understanding of the eutrophication process, which serves as a reference for implementing actions by water system managers to improve water quality in reservoirs (ARAUJO; LIMA NETO; BECKER, 2019).

This study, therefore, aimed to analyze the impacts of water quality on the water availability at three reservoirs in the State of Ceará, using the total phosphorus (TP) concentration as an indicator.

METHODOLOGY

Characterization of the study area

The present work was carried out in a sample of three reservoirs in the State of Ceará (Figure 1), selected because their catchments have distinct hydrological and physiographic characteristics: a mountainous region with a sub-humid tropical climate (Acarape do Meio basin); a transition region from a sub-humid tropical climate to a semiarid tropical climate (Aracoiaba basin); a region with a semiarid tropical climate (Pentecoste basin).

The 211-km^2 Acarape do Meio catchment belongs to the metropolitan region of Fortaleza in the Baturité Massif, drained by the Pacoti river. The Acarape do Meio reservoir has a storage capacity of 29.6 hm^3 and a maximum water surface area of 220 hectares. The region has a rainy tropical climate, with average

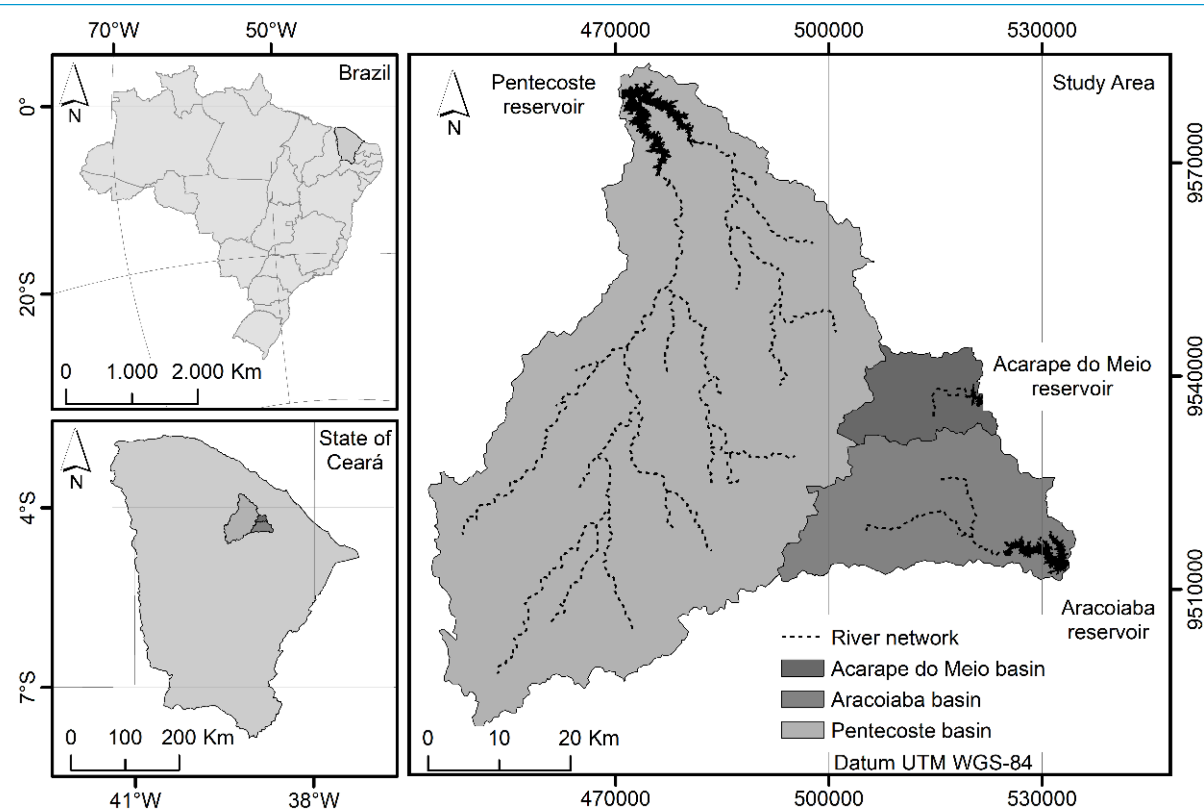

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Figure 1 – Location of the Acarape do Meio, Aracoiaba and Pentecoste catchments

annual precipitation exceeding 1,400 mm, average temperature around 21°C and potential evapotranspiration ETP of 1,400 mm. The average elevation in the watershed is 563 m, with altitudes ranging from 203 to 1,104 m. The area is characterized by a rugged relief with a mean slope of 21.5%.

The 589-km² Aracoiaba watershed also belongs to the metropolitan region of Fortaleza in the Baturité Massif. The Aracoiaba dam inundates an area of 1,614 ha, with a storage capacity of 162 hm³. The region has a rainy tropical climate, with an average temperature of 25°C, reaching values of less than 16°C in the top of the Baturité mountain range. The average annual precipitation is approximately 1,000 mm, with variations between 900 mm near the Aracoiaba dam to 1,600 mm at the headwaters of the basin, and an average evapotranspiration (ETP) of 1,500 mm. Elevations ranging from 74 to 1028 m, with an average value of 393 m, were observed at the Aracoiaba catchment. The relief is characterized by high slopes at the catchment headwaters, reaching 134% with an average value of 17%.

The 2,840-km² Pentecoste catchment belongs to the Curu river basin damming the Canindé River (a tributary of the Curu river). The Pentecoste reservoir has a storage capacity of 395.6 hm³ and a flooding area of 3,267 ha. The region has a hot semiarid tropical climate, with average annual precipitation of 800 mm, average annual ETP of 1,600 mm and average annual temperature of about 27°C.

Estimation of the total phosphorus gross load yielded in the studied catchments

Considering the lack of measured data on hydrological variables and water quality at the study areas, TP gross load was estimated based on census data on animal, agricultural and human production. Data on population and livestock and agricultural productions for the municipalities within the study areas were derived from demographic and agricultural census in 2010 and 2017, respectively. The rural population, livestock, and agricultural data were weighted by municipality fraction within the area by map overlapping.

The estimation of the TP gross load resulting from domestic sewage in the catchment was carried out by Equation 1, as follows:

$$Q_{p,dom} = (Pop).(q_{p,dom})\ (E_{ret,p}) \tag{1}$$

In which $Q_{p,dom}$: domestic sewage load in ton.year^{-1}; Pop: total number of inhabitants; $q_{p,dom}$: annual specific load of TP per inhabitant, in ton.inhab^{-1}.year^{-1}; $E_{ret,p}$: TP retention efficiency by conventional treatment methods. Specific TP loads of 0.0006 and 0.0004 ton.inhab^{-1}.day^{-1} were used for urban and rural areas, respectively (von SPERLING, 2003).

For estimating TP gross load by livestock farming in the catchment, Equation 2 was used:

$$Q_{p,dom} = (Reb).(\ q_{p,pec}) \tag{2}$$

In which $Q_{p,dom}$: TP gross load produced by livestock, in ton.year^{-1}; Reb: animal population in number of heads; $q_{p,pec}$: annual specific load of TP per animal unit, in ton.head^{-1}.year^{-1}, calculated as a function of the average production of manure per animal unit and the average percentage of TP in the manure. According to Boyd (1971) and Esteves (1998), average daily production of manure per animal unit is estimated to be 10 kg.day^{-1} for cattle, horse, donkey or mule, 2.5 kg.day^{-1} for swine, 1 kg.day^{-1} for sheep or goat, and 0.18 kg.day^{-1} for poultry. Average percentages of TP from animal manure were proposed by Lacerda and Sena (2005), with 0.4% for cattle, horse, donkey or mule, 0.35% for swine, 0.50% for sheep or goat, and 1.3% for poultry. Thus, the TP gross load derived from agriculture was computed by Equation 3, as follows:

$$Q_{p,agr} = (NN).(A_p).(P_{soil}).(P_{culture}) \tag{3}$$

In which $Q_{p,agr}$: TP gross load o produced by livestock, in ton.year^{-1}; NN: total nutritional need per crop, in ton.ha^{-1}; A_p: annual planted area per crop, in ha.year^{-1}; P_{soil}: phosphorus loss depending on the soil type, in percentage; $P_{culture}$: phosphorus loss depending on the crop, in percentage. The reference values of nutritional needs for crops i were derived from UFC (1993). The percentages of phosphorus loss to the soil can be found in Lacerda and Sena (2005), while average loss rates of nutrients from agricultural crops to the environment were proposed by Malavolta and Dantas (1980) and Vollenweider (1968).

Estimation of total phosphorus input load into the reservoirs

TP input load into the reservoir was derived from measured concentration data in the water body by water and TP balance. For this, the transient complete-mix model proposed by Vollenweider (1968) (CHAPRA, 2008) was applied, based on Equation 4.

$$P(t) = P_o \cdot e^{-\left(\frac{Q_s}{V}+K_r+K_s\right).t} + \frac{W}{\left(\frac{Q_s}{V}+K_r+K_s\right).V} \cdot \left[1- e^{-\left(\frac{Q_s}{V}+K_r+K_s\right).t}\right] \tag{4}$$

In which P(t): TP concentration in the reservoir (kg.m-3); P_o: initial TP concentration in the reservoir (kg.m^{-3}); t: elapsed time (year); V: average reservoir volume for a specific period (m³); W: TP input load of the influent (kg.year^{-1}); Q_s: reservoir outflow (m³.year^{-1}), considering spills, evaporation and regularization by water intake devices; K_r: reaction coefficient (s^{-1}); K_s: phosphorus decay coefficient (s^{-1}). In Equation 4, the sum of the Qs/V (detention time), K_r, and K_s parameters is known as λ factor, and can be simplified by admitting the value of the reaction coefficient K_r as negligible.

Some studies have proposed equations to estimate K_s as a function of the average water residence time in the reservoir RT, as generalized in Equation 5, with the inclusion of an adjustment coefficient α. RT is computed by dividing the storage capacity by the average annual outflow measured for each reservoir and periods with different hydrological regimes (2004–2010 and 2011–2020). Vollenweider (1976), for example, adjusted an equation based on data from temperate lakes and found α equal to one. Salas and Martino (1991) proposed a value of α of two in an equation adjusted to data from 40 tropical lakes. Toné and Lima Neto (2020) found α equal to four in the semiarid region of Ceará.

$$K_s = \alpha/\sqrt{RT} \tag{5}$$

Considering that RT can be influenced by hydrological regimes, this research proposes a method for calibrating α to different areas (Acarape do Meio, Aracoiaba e Pentecoste catchments) and distinguishing between wet (2004 to 2010) and dry periods (2011 to 2020). To estimate the average concentration of TP to the Acarape do Meio, Aracoiaba and Pentecoste reservoirs, data on TP concentration measured at sampling points distributed in these water bodies (Figure 2) were analyzed. It was assumed, therefore, that the average concentration of TP at the point located most upstream of the reservoir will be the reference concentration of TP input into that water body.

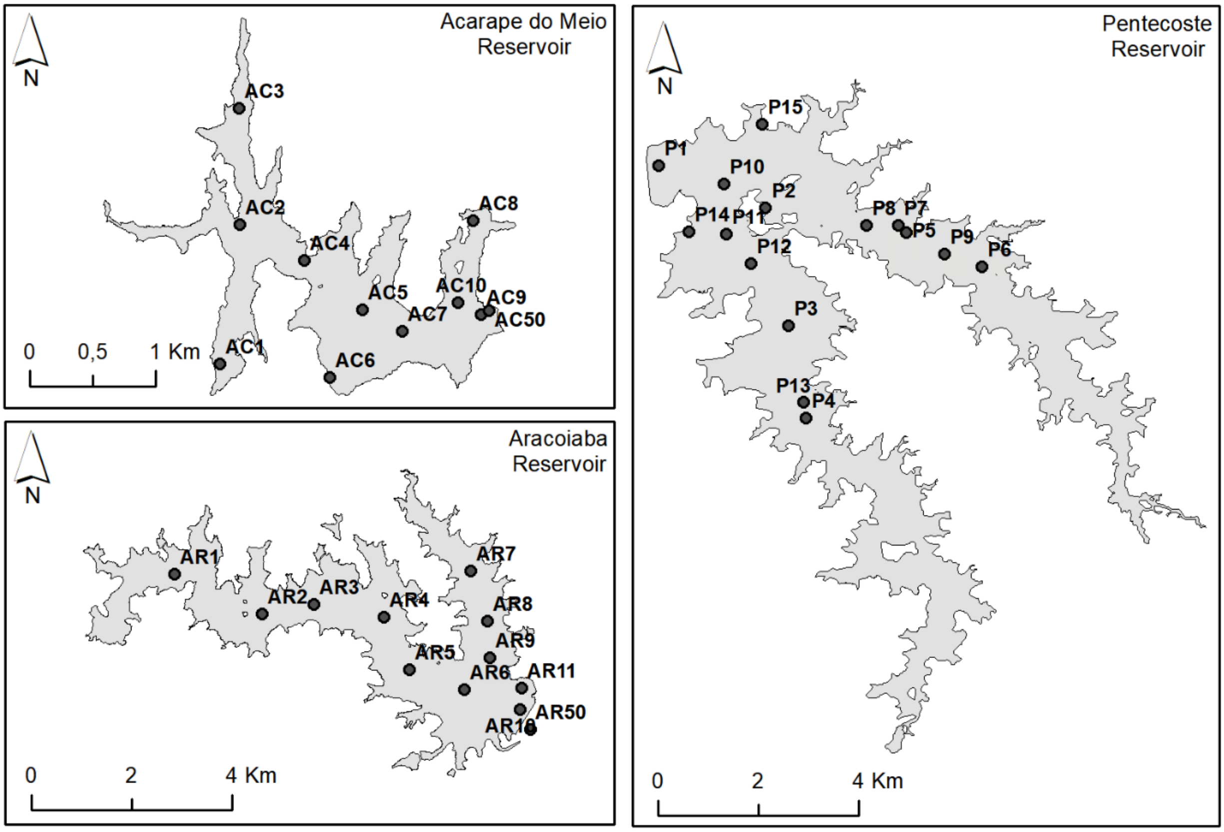

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Figure 2 – Location of sampling points for estimating total phosphorus concentrations in the Acarape do Meio, Aracoiaba and Pentecoste reservoirs (Datum UTM WGS84 zone 24M).

RESULTS AND DISCUSSION

Total phosphorus gross load yielded in the catchments

The estimation of TP gross load related to domestic, livestock and agricultural activities is detailed in Table 1. The results concerning domestic activities indicated annual values of TP gross load ranging from 12 to 40 ton.year^{-1}, for the study areas. The results also show that the Acarape do Meio catchment yielded the highest specific TP gross load (59 kg.km^{-2}.year^{-1}), when compared to the Aracoiaba (50 kg.km^{-2}.year^{-1}) and Pentecoste (12 kg.km^{-2}.year^{-1}) catchments, which can be explained by the fact that it has the highest demographic density among the study areas (123 inhab.km^{-2}).

Concerning livestock activities, the Acarape do Meio catchment has once again the highest TP gross load per unit area (604 kg.km^{-2}.year^{-1}), considering its higher density of livestock production, with 324 animal units.km^{-2}, against 215 animal units.km^{-2} in the Aracoiaba catchment and 69 animal units.km^{-2} in the Pentecoste catchment.

Regarding agricultural production, the Aracoiaba catchment yielded the highest TP gross load with 19 ton.year^{-1} (32 kg.km^{-2}.year^{-1}), against 5 ton. year^{-1} (22 kg.km^{-2}.year^{-1}) for the Acarape do Meio catchment e 17 ton.year^{-1} (5 kg.km^{-2}.year^{-1}) for the Pentecoste catchment. The highest TP load observed in the Aracoiaba catchment may be explained by the intense agricultural use of the region (9,007 ha.year^{-1} in Aracoiaba, against 2,563 ha.year^{-1} in Acarape do Meio and 7,504 ha.year^{-1} in Pentecoste).

Total phosphorus input into the reservoirs

To estimate the TP input load into the reservoirs, two periods with distinct hydrological regimes were analyzed: the period 2004–2010, characterized by regular rains with above-average precipitation in several of these years and higher water fluxes; and the period 2011–2020, marked by a severe drought that lasted almost the entire decade and resulted in low levels of water accumulation in reservoirs over several years.

Data on TP concentrations were provided by the Water Resources Management Company — COGERH. According to the data, TP concentrations of samples collected in the most upstream points of the Acarape do Meio (Point AC2) and Pentecoste (Points P04 and P06) reservoirs (see Figure 2), correspond to the 68.2 and 69% quantile of those measured in the vicinity of the dam. Therefore, the results indicated that TP concentrations closer to the reservoir inlet, under the strong influence of the river regime and TP load input, are relatively higher. TP concentrations in the Aracoiaba reservoir, however, were restricted to points located closer to the dam and, therefore, it was not possible to carry out such an analysis. Considering the scarcity of measured data on TP input load into reservoirs of the region, a reference TP concentration was adopted at the reservoir inlet, corresponding to the 70% quantile (P70%) of the measured TP concentrations in the vicinity of the dam.

TP input loads were then estimated using the reference TP concentration represented by the 70th quantile (P70%) and the annual inflow discharges derived from reservoir water balance carried out for both time periods (2004–2010 and 2011–2020), as detailed in Table 2. The reference TP concentrations varied from

Table 1 – Estimate of total phosphorus gross load derived from domestic, livestock and agricultural activities in the study areas.

Activity	Variables	Catchments		
		Acarape do Meio	Aracoiaba	Pentecoste
Domestic	Urban population	12,766	35,119	49,528
	Rural population	13,301	24,472	30,132
	Total inhabitants	26,067	59,591	79,660
	Demographic density	123	101	24
	TP gross load (ton.year^{-1})	12	30	40
	Specific TP gross load (kg.km^{-2}.year^{-1})	59	50	12
Livestock	Cattle (or similar) population	4,358	4,357	17,648
	Swine population	8,020	4,441	23,548
	Sheep and goats population	2,350	4,054	44,069
	Poultry population	53,903	113,683	138,314
	Total animal population	68,631	126,535	223,579
	TP gross load (ton.year^{-1})	128	172	488
	Specific TP gross load (kg.km^{-2}.year^{-1})	604	293	150
Agriculture	Maize planted area (ha)	978	4,157	3,826
	Black-eyed beans planted area (ha)	429	2,912	3,370
	Fava beans planted area (ha)	619	1,080	84
	Manioc planted area (ha)	46	77	9
	Rice planted area (ha)	168	192	25
	Melon planted area (ha)	0	34	0
	Pumpkin planted area (ha)	55	135	144
	Watermelon planted area (ha)	3	35	11
	Sugar cane planted area (ha)	29	92	7
	Green beans planted area (ha)	236	293	28
	Total planted area (ha)	2,563	9,007	7,504
	TP gross load (ton.year^{-1})	5	19	17
	Specific TP gross load (kg.km^{-2}.year^{-1})	22	32	5

Table 2 – Estimated total phosphorus load into the Acarape do Meio, Aracoiaba and Pentecoste reservoirs for the periods 2004–2010 and 2011–2020.

Parameter	Acarape do Meio		Aracoiaba		Pentecoste	
	WP[1]	DP[2]	WP[1]	DP[2]	WP[1]	DP[2]
Annual inflow volume (hm^3.ano^{-1})	54.3	18.9	74.0	31.3	461.3	33.6
Mean reservoir volume (hm^3)	22.4	14.5	147.1	66.6	231.5	59.2
TP concentration – reservoir (mg.L^{-1})	0.232	0.158	0.085	0.097	0.135	0.160
TP concentration – inlet (mg.L^{-1})	0.140	0.083	0.069	0.070	0.101	0.107
TP input load (ton.ano^{-1})	12.6	3.0	6.3	3.0	62.3	5.4

[1] WP: wet period (2004–2010), [2]DP: dry period (2011–2020)

0.085 to 0.320 and period. TP concentrations at the reservoirs' inlets are within the range of values reported by Bieroza and Heathwaite (2015) (0.007 – 1.097 mg.L^{-1}), Chen *et al.* (2015) (0.010 – 0.200 mg.L^{-1}), Bowes *et al.* (2015) (0.085 – 0.447 mg.L^{-1}), Rattan *et al.* (2017) (0.055 – 1.740 mg.L^{-1}).

Using the reference TP concentrations at the reservoir inlet (computed based the 70% quantile criterion, as explained previously), TP input loads into the reservoirs were estimated for the wet (2004–2010) and dry (2011–2020) periods, with values varying from 3 ton.year^{-1} (14.1 kg.km^{-2}.year^{-1}) to 62.3 ton. year^{-1} (293.8 kg.km^{-2}.year^{-1}). The wet period presented higher TP input loads to the three reservoirs, as highlighted for the Pentecoste catchment with an annual input almost 12 times higher when compared to the prolonged dry period. TP input loads into Acarape do Meio were also estimated for the wet and dry periods, with 12.6 and 3.0 ton.year^{-1}, respectively. Rocha and Lima Neto (2021) found a TP input load into the Acarape do Meio reservoir of 8.3 ton.year^{-1} for the period 2008–2020, corroborating the results of this research.

To calibrate α applying Equations 4 and 5, the reference concentrations P50% and P70% and average annual TP loads related to both time periods and reservoirs were used (Table 3). The results show that the variables used are highly influenced by the hydrological regimes related to both periods. The discrepancies in RT are quite high for different hydrological regimes, especially in the Aracoiaba (about seven times higher) and Pentecoste (almost 20 times higher) reservoirs, where the effects of prolonged drought in the most recent period (2011–2020) were more evident, increasing RT.

According to Table 3, values of α after calibration ranged from 0.40 to 3.13, depending on the reservoir and hydrological regime considered. Note that α tends to be closer to 1 as proposed by Vollenweider (1976) in the period of hydrological regime with above-average rainfall and higher surface runoff generation (2004–2020), presenting characteristics of regions with temperate climate. On the other hand, α is within the range between 2 and 4 in the period of prolonged drought (2011–2020), which occurs more often in regions of tropical climate with higher aridity characteristics, such as suggested by Salas and Martino (1991) and Toné and Lima Neto (2020).

Considering that only a fraction of the TP gross load produced in a river basin reaches the outlet reservoir, the PIR was computed, having been defined as a ratio between the TP input load into a reservoir and the TP gross load derived from domestic, agricultural and livestock farming production generated in the catchment, as presented previously. Based on the assumption that the hydrological regime can influence the phosphorus transport conditions, a correlation between PIRs and surface runoff coefficients was established using values from different periods (2004–2010 and 2011–2020) and study areas (Acarape do Meio, Aracoiaba and Pentecoste catchments), as illustrated in Figure 3. The results indicated a good correlation between PIR and the surface runoff coefficient, with R^2 of 0.96. Despite using few points, the results indicate a tendency for PIR to increase in hydrological regimes with higher surface runoff.

Water availability at the reservoirs based on quality scenarios

To model the dynamics of TP in the reservoirs, the Chapra phosphorus balance model (CHAPRA, 2008) was applied for the period 2011–2020 with measured TP concentrations available for each reservoir. For that, the model simulated an average annual TP load entering the reservoir with different stored volume fractions (1, 5, 10, ..., 100%) to evaluate its effects on TP concentrations at the reservoir. Results of the TP balance can be seen in Figure 4, indicating a trend towards higher concentrations of TP for smaller reservoir volumes, as evidenced by measured data available at the three reservoirs. Values of TP concentrations (measured and modeled) shown in Figure 4 often exceeded the quality limits of class 3, defined according to Brazil's Environment Council (CONAMA) Resolution nº 357/2005 (BRASIL, 2005), especially for smaller water volumes, indicating low quality regarding phosphorus, which can be a result of the long period of drought and prolonged RT.

For analyzing the impacts of water quality on the water availability of reservoirs, a simulation was carried out considering three different flow regularization scenarios based on the levels of TP concentration at the reservoirs, as follows: water release condition to meet demands without quality restrictions, as it is usually carried out in reservoirs in the State of Ceará (Scenario 1); b) water release condition as long as the water quality does not exceed the quality limit of class 3 regarding TP concentrations (Scenario 2); and c) water release condition as long as the water quality does not exceed the quality limit of class 2 regarding TP concentrations (Scenario 3).

To evaluate the impacts on water quality based on TP concentrations, the water yield with 90% reliability level for Scenarios 2 and 3 (Q_{90}, with quality constraints) normalized in relation to the reference water yield for Scenario 1 ($Q_{90,ref}$, without quality constraints) for different conditions of TP input load as a percentage of the total load estimated for the periods 2004–2010 and 2011–2020 was plotted in Figure 5. The results showed that keeping the same TP input load estimated for the period 2004–2010 regulated flows under the quality limits of class 2 and 3 would not be feasible. To release a minimum of 50%

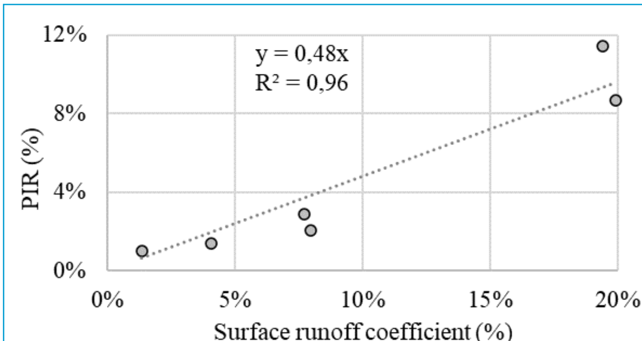

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Figure 3 – Relationship between the Phosphorus Input Ratio (PIR) and the surface runoff coefficient in the Acarape do Meio, Aracoiaba and Pentecoste catchments for the periods of 2004-2010 and 2011-2020.

Table 3 – Calibration of adjustment coefficient α and estimation of other parameters used in the total phosphorus balance in the Acarape do Meio, Aracoiaba and Pentecoste reservoirs for the periods 2004-2010 and 2011-2020.

Reservoir	Period	RT (years)	λ (year^{-1})	K_s (year^{-1})	α
Acarape do Meio	2004-2010	0.49	4.41	2.35	1.64
	2011-2020	1.48	2.53	1.86	2.26
Aracoiaba	2004-2010	2.48	0.66	0.25	0.40
	2011-2020	17.74	0.65	0.59	2.50
Pentecoste	2004-2010	0.82	2.77	1.55	1.40
	2011-2020	15.86	0.85	0.79	3.13

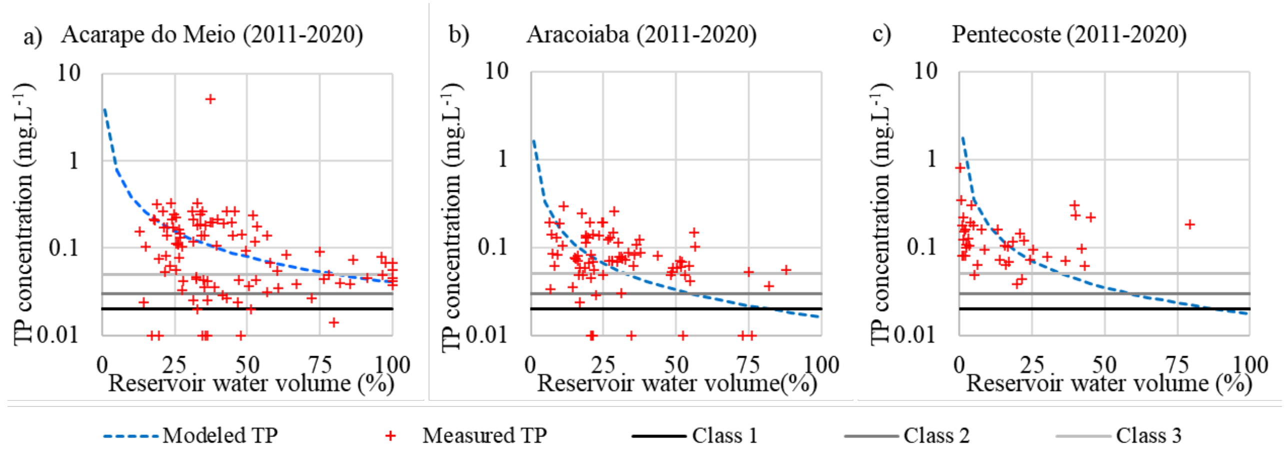

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Figure 4 – Measured (red markers) and modeled (blue dashed line) TP concentrations for the period 2011-2020 as a function of water stored volumes in the reservoirs: a) Acarape do Meio, b) Aracoiaba; and c) Pentecoste.

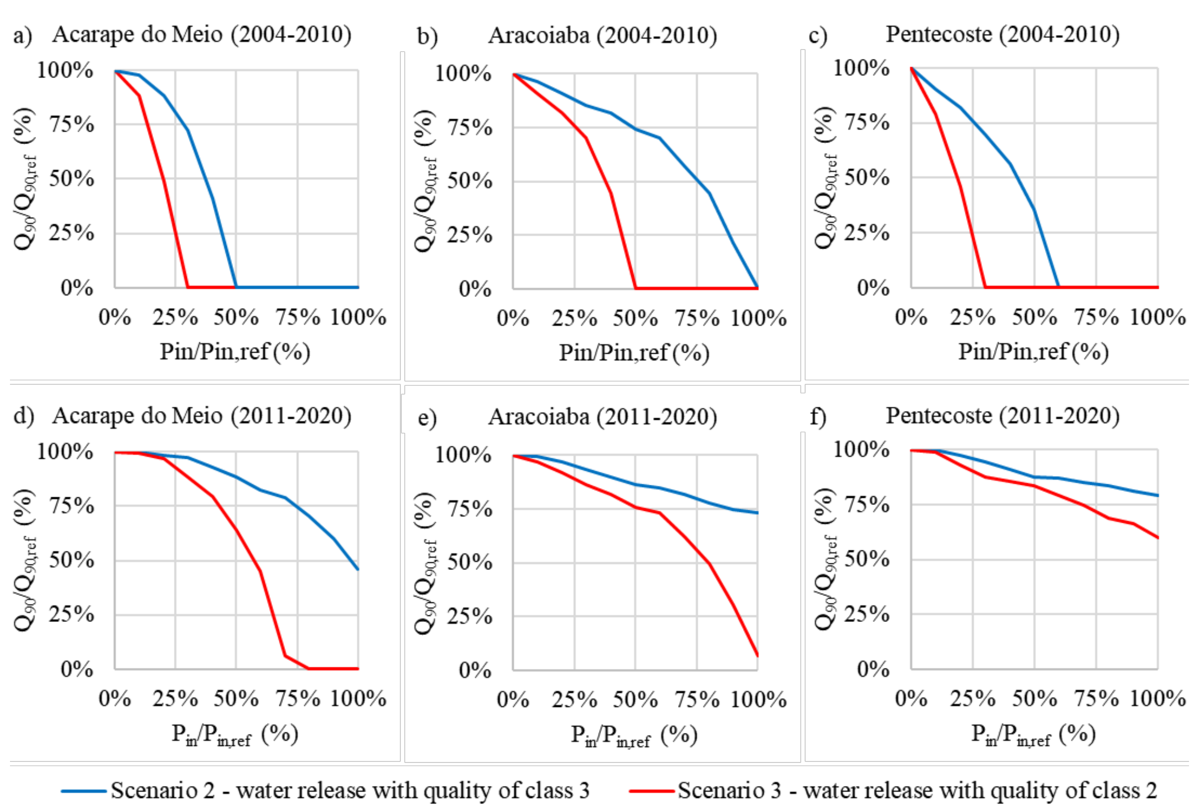

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Figure 5 – Normalized water yield with 90% reliability level (Q_{90}) for Scenarios 2 (blue line) and 3 (red line) in relation to the reference water yield for Scenario 1 ($Q_{90,ref}$) for different conditions of TP input load as a percentage of the total load estimated for the study areas and periods: a) Aracape do Meio (2004-2010); b) Aracoiaba (2004-2010); a) Pentecoste (2004-2010); d) Aracape do Meio (2011-2020); Aracoiaba (2011-2020); and Pentecoste (2004-2010).

of the reference water yield ($Q_{90,ref}$, without quality restriction — Scenario 1), keeping the quality limit of class 2 (Scenario 3), it would be necessary to reduce the TP load to 20, 38 and 19% of those estimated for this same period (2004–2010) at the Acarape do Meio, Aracoiaba and Pentecoste reservoirs, respectively. On the other hand, to release 50% of the reference water yield ($Q_{90,ref}$) with quality limit of class 3 (Scenario 2), the TP input load must be reduced to 37, 76 and 43% of those estimated in the Acarape do Meio, Aracoiaba and Pentecoste reservoirs, respectively.

Assuming the same TP input load estimated for the period 2011–2020 (with loads 4.2, 2.1 and 11.6 times lower than in the period 2004–2010 for the Acarape do Meio, Aracoiaba and Pentecoste catchments, respectively) and water volume evolution by regular drawing up and down the reservoir as observed in semiarid reservoirs, a better water quality would be achieved according to the water and TP balance modelling (Figure 5). The results show that one may release water with class 3 quality (Scenario 2) from all reservoirs without any reduction in the TP input load. By reducing the TP input load to 50% of that estimated for the period 2011–2020, at least 64% of the reference water yield ($Q_{90,ref}$) for any scenario with quality restrictions (Scenarios 2 and 3) and reservoirs could be released from the reservoirs, reaching 88% of $Q_{90, ref}$ for the Pentecoste reservoir with quality constraints of class 3 (Scenario 2).

According to the results presented in Figure 5, it may be observed that changes on TP input loads can impact water availability in the reservoirs by assuming water quality criteria to regulate flows. To minimize such impacts, adoption of domestic and industrial effluent management techniques such as the installation of Sewage Treatment Plants (STP), efficient in removing pollutants, controlled use of pesticides and fertilizers and use of biodigesters to produce gas and fertilizer from animal waste could reduce the TP input load into the reservoirs and guarantee the use of water with better quality.

CONCLUSIONS

Estimating TP input load into the reservoirs by combining TP gross loads in the study areas derived from data on population, livestock and agricultural productions available on demographic and agricultural census with the PIR proved to be a simple and effective strategy. The PIR concept, proposed in this study, presented a good adjustment with surface runoff coefficients, by incorporating hydrological characteristics of the study areas.

The modeling of TP balance based on Chapra's complete mixing equation allowed estimating a decay relationship of TP concentrations for larger stored volumes, following the same behavior observed for measured TP data available for the three reservoirs. Furthermore, the relationship between the phosphorus decay coefficient Ks and the hydraulic retention time (RT) presented different adjustment coefficients α, depending on the hydrological regimes in the study areas.

This research also analyzed the effects of including water quality restrictions regarding TP content on water availability at the reservoirs (Acarape do Meio, Aracoiaba and Pentecoste). According to the results, TP concentrations at the reservoirs can negatively impact water availability subject to quality constraints of classes 3 and 2 (Scenarios 2 and 3, respectively), established according to the CONAMA Resolution nº 357/2005 (BRASIL, 2005). Considering TP input loads into the reservoirs such as those observed in the period 2004–2010 already makes the adoption of quality criteria for regulating class 3 water (Scenario 2) or class 2 (Scenario 3) unfeasible. Therefore, the adoption of techniques to reduce the production and export of phosphorus from the study areas is extremely important for making water available within the quality standards required by CONAMA.

This strategy of including quality criteria for water supply from strategic reservoirs in the State of Ceará should be considered by the water resources decision makers to identify dams with use restrictions due to water quality, even if they have enough stored volumes.

AUTHORS' CONTRIBUTIONS

Da Silva, A.J.P.: Data Curation, Investigation, Methodology, Writing – Original Draft. Cavalcante, L.D.: Visualization, Writing – Review & Editing. Mamede, G.L.: Conceptualization, Project Administration, Supervision.

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