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EARTH SCIENCES

Modelling the impact of sediment management on the trophic state of a tropical reservoir with high water storage variations

CAMILA C.S LIRA, PEDRO H.A. MEDEIROS & IRAN E.L. NETO

Abstract: Eutrophication of lakes has affected society in many regions, particularly in water scarce environments where: i) low runoff reduces the self-purification potential of water bodies; ii) water supply relies on surface reservoirs, which are susceptible to nutrient enrichment. This work presents an assessment of the impact of the silted sediment management on the trophic status of a tropical surface reservoir with intense temporal variability of water storage. A complete mixing model describing the total phosphorus budget in the water and sediments was used, based on semi-empirical formulations. The sediment reuse as soil fertilizer has been proposed to increase productivity in small scale agriculture, which should also enhance the water quality by removing the nutrient-enriched sediment from lakes. Model application for a 40-years period indicate that sediment management may improve water quality, changing from poor to acceptable trophic state during roughly 10% of the time when the reservoir is not empty.

Key words: Water-sediment interaction, sediment reuse, eutrophication, water quality modelling, tropical reservoir.

INTRODUCTION

Human settlements situated in water scarce environments have developed techniques to adapt to droughts, with the construction of dams being a common alternative for water supply in such regions, as in the tropical Northeast of Brazil (Campos 2015).

Water stored in surface reservoirs is very vulnerable to quantity reduction and quality degradation as a result of sediment transfer from the catchment to the lake, among other processes. Quantitatively, sediment deposition results in a reduction of the stored capacity and modification of the reservoir geometry, making it shallower and therefore more susceptible to evaporation losses (de Araújo et al. 2006). Qualitatively, the sediment eroded from the topmost soil layers is rich in nutrients, and when deposited in reservoirs, leads to acceleration of the eutrophication process (Conley et al. 2009, Maavara et al. 2015). For instance, in the Federal State of Ceará, Brazil, where the present study was conducted, among the 155 strategic surface reservoirs monitored by the local Water Resources Management Company (COGERH), 80% were classified as eutrophic or hypereutrophic according to a bulletin released in August 2017, after the region has suffered from a 5-years drought.

Reduction of erosion (Santos et al. 2017) and sediment transfer (Medeiros et al. 2014) have been pointed out as efficient on controlling reservoirs siltation, thus increasing reservoir's lifetime and reducing the severe socioeconomic impacts caused by their degradation. However, the territorial coverage of inadequate land use, which usually exceeds the operational capacity of the environmental agencies, requires also the adoption of corrective measures to maintain water availability at desired levels.

Reuse of sediment deposited in surface reservoirs have been proposed for soil restoration (Yozzo et al. 2004, Bondi et al. 2016) and as a nutrient source to the agricultural sector (Fonseca et al. 1998, Sigua 2009, Braga et al. 2017), which contributes to a circular economy philosophy (Stahel 2016). A cost-benefit analysis indicates that, compared to conventional soil fertilization, nutrient recycling from sediments may generate savings of up to 25% in the Northeast region of Brazil, where there is a dense reservoir network (Braga et al. 2019). Additionally, an improvement of the trophic state of surface reservoirs is expected due to the removal of the nutrient enriched sediment, which represents a potential source of phosphorus to the water (Chowdhury and Bakri 2006).

Phosphorus metabolism in reservoirs and interactions among water and sediment, regarding its fluxes on inorganic, dissolved organic and particulate organic forms, have been well described in the literature. Phosphorus is adsorbed to inorganic matter, especially mineral clay, depending on the environmental conditions of the aquatic system, such as redox conditions, pH and the phosphorus concentration in the water and sediment (Fragoso Júnior et al. 2009). The presence of iron and aluminium increases the sediment capacity of adsorbing phosphorus, and it has also been reported that Ca^{2+} and Mg^{2+} contribute to phosphorus adsorption (Wiegand et al. 2014). However, because they can be consumed by phytoplankton, their concentration in the sediment can be easily reduced. Phosphorus recycling from the sediment layer to the water column is highly dependent on the sediment-water interface concentration gradient (Fragoso Júnior et al. 2009), and also a function of the Fe:P molar ratio in the sediment (Jensen et al. 1992).

The importance of nutrient enrichment to degradation of surface water bodies, as well as the need to adopt control measures to keep water quality at acceptable levels, led to the development of long-term models of phosphorus concentration in lakes. Vollenweider (1976) proposed a model, based on the water residence time, to assess eutrophication status, and since them, other modelling approaches have been applied worldwide. Chapra and Canale (1991) developed a two-layer phosphorus model, explicitly introducing the phosphorus exchange in the water-sediment interface, and highlighted the importance of temperature on the phosphorus fluxes. Furthermore, the Lake Ecosystem Effect Dose Sensitivity (LEEDS) model predicts phosphorus content in nine different lake compartments: dissolved, colloidal and particulate phosphorus in surface water and deep water, as well as phosphorus in sediments (areas of erosion, sediment transport and fine sediment accumulation) and phytoplankton (Malmaeus et al. 2006). Other advances on estimation of lake phosphorus content comprehend numerical modelling (for instance, Chao et al. 2006) and site-specific adaptations of previous models (Chapra et al. 2016).

Among the limitations of the studies on nutrient retention in lakes and reservoirs, Cook et al. (2010) argue that most assessments derive from temperate climate regions and are often short-term (1-2 years). These features hamper a direct use of the available models to tropical conditions, where reservoirs usually suffer strong water storage variations (against the hypotheses of many available models, of lake constant volume) and are susceptible to lower temperature fluctuations among seasons.

In this work, the impact of sediment management practices on the water quality of a tropical reservoir was assessed with the model proposed by Chapra and Canale (1991), which describes the budget of total phosphorus in water and sediments through semi-empirical formulations adopting complete mixing in the lake. The original model was adapted in this work to account for the extremely high temporal variability of the stored water volume, as well as a more practical method for the parameterization.

The two-layer (water and sediment) phosphorus budget model adapted to tropical conditions was run for a surface reservoir (roughly 1x10^6 m³ storage capacity, located in the water scarce Northeast of Brazil) over a 40-years period to compare the current status with that expected with the adoption of sediment management practices, assessing the effects of seasonality on the reservoir trophic state. For model parameterization and reservoir characterization, field campaigns were carried out to measure phosphorus content in the water and sediments, as well as to survey the Tijuquinha reservoir bed.

MATERIALS AND METHODS

Study area

The study was conducted in the Tijuquinha reservoir, located in the tropical Northeast of Brazil in the mountainous region of Baturité, with a 38.0 km² contributing catchment (Figure 1). The original storage capacity in 1917 was 9.7 x 10^5 m³, but a bathymetric survey carried out in 2016 indicated a reduction of roughly 40%, with the current capacity being 5.8 x 10^5 m³ (Lira et al. 2018). Along with the population growth of the city of Baturité – currently with approximately 25,000 inhabitants – the siltation of the Tijuquinha reservoir led to frequent water supply failure of that city. A complementary water supply system located downstream of the city was built, increasing the power demand to pump water to Baturité when the Tijuquinha reservoir gets empty.

The climate is hot sub-humid tropical corresponding to the central part of the Baturité Massif, associated with a dense vegetation characteristic of the Atlantic Forest (Bétard 2012). The rainfall is concentrated in a rainy season running from February to May, but the annual rainfall distribution is also induced orographically by the existence of the Baturité Massif, acting as a mountainous barrier to the trade winds. The average monthly temperatures range from 17.5 to 25.2 °C, with annual precipitation and potential evaporation of approximately 1,700 and 1,000 mm/year, respectively.

Intermittency of the streams due to the temporal concentration of rainfall results in strong intra-annual variation of the water volumes stored in the Tijuquinha reservoir, with its dynamics following seasonality of the rainfall. This feature is shown in Figure 2, from which one can depict that in the first semester of the year the reservoir usually gets full and dries out in the second semester.

Water-sediment interaction phosphorus model adapted for tropical conditions

The water-sediment interaction model proposed by Chapra and Canale (1991) simulates the total phosphorus fluxes among the water and sediment layers based on semi-empirical formulations and considering complete mixing in the lake, as expressed in Equations 1 and 2 and illustrated in Figure 3.

$$V_1 \frac{dp_1}{dt} = W - Qp_1 - v_s A_2 p_1 + v_r A_2 p_2 \quad (1)$$

$$V_2 \frac{dp_2}{dt} = v_s A_s p_1 - v_r A_2 p_2 - v_b A_2 p_2 \quad (2)$$

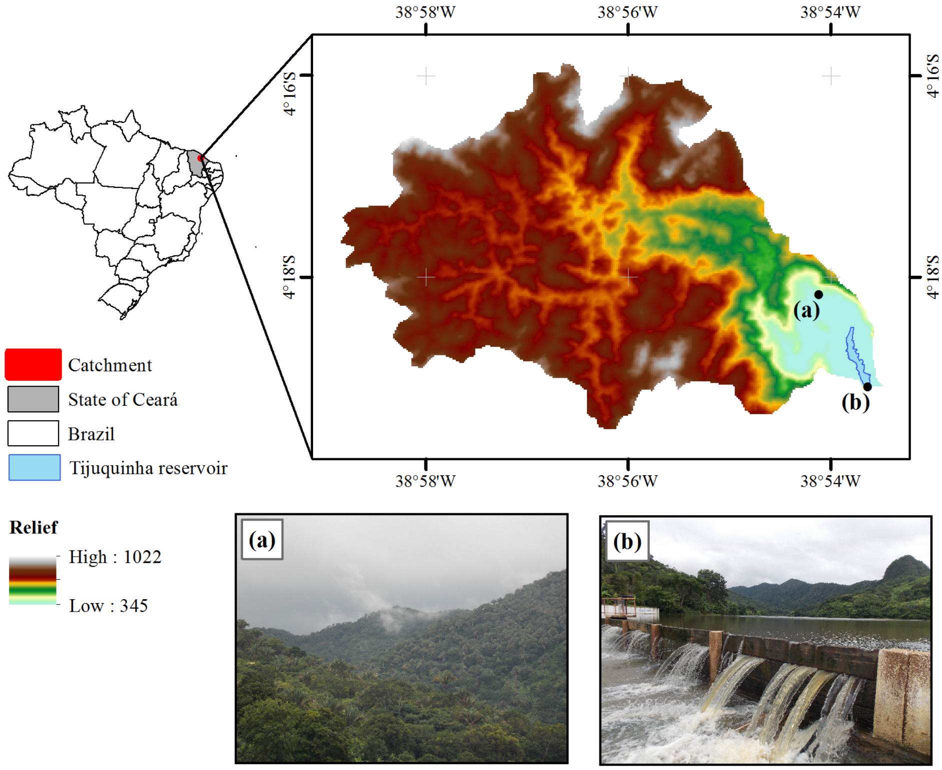

Figure 1. Location map of the Tijuquinha reservoir, its catchment and local features as the relief and vegetation.

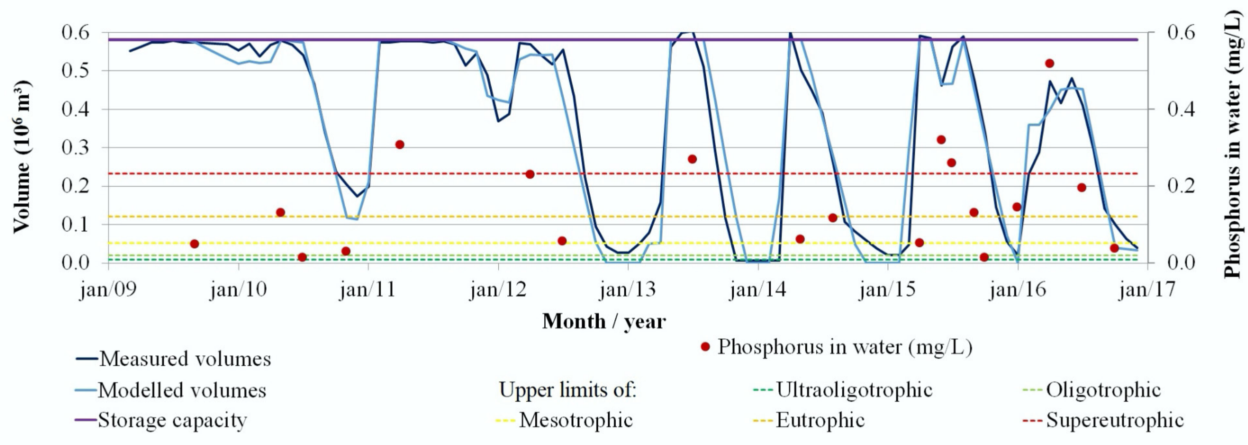

Figure 2. Seasonality of the water volumes stored in the Tijuquinha reservoir and measured phosphorus concentrations in the period 2009-2016.

where: subscripts 1 and 2 are related to the water and the enriched surface sediment layer, respectively; V_1 is the reservoir volume (m^3); V_2 is the sediment volume (m^3); t is the time (month); W is the phosphorus load to the lake (mg/month); Q is the outflow (m^3/month); p_1 is the phosphorus concentration in the water (mg/m^3); p_2 is the phosphorus concentration in the sediment (mg/m^3); v_s is the phosphorus apparent settling velocity from the water to the sediment (m/month); v_r is the coefficient of phosphorus recycled mass-transfer from the sediments

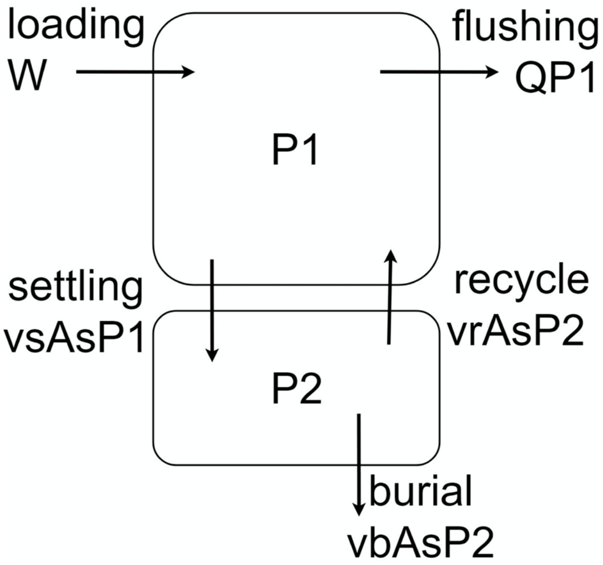

Figure 3. Diagram of the water-sediment phosphorus budget model (Chapra and Canale 1991) and the respective loads' quantification (adapted from Chapra and Canale 1991).

to the water (m/month); v_b is the phosphorus burial velocity to deep sediments (m/month); A_2 is the surface area of the deposition zone (m²).

Chapra and Canale (1991) proposed the phosphorus budget model for virtually constant reservoir volumes, therefore the water and sediment volumes (V_1 and V_2, respectively) are allocated outside the derivative (Equations 1 and 2). However, for the hydrological conditions in the tropical region, where there is high variation of the stored volumes in the reservoirs, such variables must be allocated within the derivative for coherence. Additionally, the temporal resolution of the simulations was increased in this study, from a yearly timestep – as proposed initially by Chapra and Canale (1991) – to a monthly timestep (as indicated in equations 1 and 2), in order to capture the strong intra-annual variability in the studied reservoir.

The phosphorus budget in the water of lakes in tropical region was then modified according to Equation (3), which was solved on Eulerian form to obtain the phosphorus concentration at each time step (Equation 4).

$$\frac{dV_1 p_1}{dt} = W - Qp_1 - v_s A_2 p_1 + v_r A_2 p_2 \tag{3}$$

$$p_{1(t+1)} = \frac{V_1 p_{1(t)} + \left(W - Qp_1 - v_s A_2 p_1 + v_r A_2 p_2\right)\cdot \Delta t}{V_{1(t+1)}} \tag{4}$$

The computation comprised a 3-steps scheme:

1) Phosphorus input mass to the lake is mixed to that present at the start of the time-step and the reservoir water volume (V_1') and phosphorus concentration (p_1') are computed according to Equations 5 and 6.

$$V_1' = V_1 + V_{in} \tag{5}$$

$$p_1' = \frac{W + V_{in} p_{in}}{V_1'} \tag{6}$$

2) Interaction between the water column and the sediment is simulated and the phosphorus concentration (p''_1) is updated based on Equation 7.

$$p_1'' = p_1' + \frac{\left(-v_s A_2 p_1' + v_r A_2 p_2\right)\cdot \Delta t}{V_1'} \tag{7}$$

3) Quantification of the phosphorus load left from the system ($Q{\cdot}p_1''$) and estimation of the final phosphorus concentration in the water [$p_{1(t+1)}$], according to Equation 8.

$$p_{1(t+1)} = \frac{p_1'' V_1' - \left(Q\cdot\Delta t\right) p_1''}{V_1' - \left(Q\cdot\Delta t\right)} \tag{8}$$

For the sediment layer, the same procedure proposed by Chapra and Canale (1991) was adopted, with a constant sediment volume calculated as the product of the reservoir sedimentation area by a sediment layer (h_2) with 10 cm thickness. The Eulerian solution of the phosphorus budget in the sediment layer is presented in Equation 9.

$$p_{2(t+1)} = p_{2(t)} + \frac{\left(v_s A_2 p_1' - v_r A_2 p_2 - v_b A_2 p_2\right) \cdot \Delta t}{A_2 h_2} \qquad (9)$$

In order to obtain the water volumes stored in each time step of the simulations, a water balance was computed in the reservoir, as presented by de Araújo et al. (2006) (Equation 10).

$$\frac{dV}{dt} = \left(Q_A + Q_H\right) - \left(Q_E + Q_S + Q_W\right) \qquad (10)$$

where: V is volume (m³); t is time (month) and the other variable are flows (m³/month): Q_A is inflow from the river network; Q_H is water input by rainfall directly on the reservoir surface; Q_E is water loss due to evaporation; Q_S is reservoir outflow by spillage; Q_W is the water withdrawn from the reservoir for supply. Water fluxes between the reservoir and the bedrock was considered negligible, according to the recommendation of de Araújo et al. (2006).

Model validation was performed for a simulation in the period from 2009 to 2016, during which biannual phosphorus concentrations were measured by the Companhia de Gestão dos Recursos Hídricos do Ceará - COGERH. The model performance was assessed by: statistical bias (b), mean absolute error (A), root mean square error (E), ratio between modelled and observed standard deviations (R_σ), mean absolute error of deviations (A_d), root mean square error of the deviations (E_d), Willmott's concordance index (d) and Pearson's correlation index (r).

The calibrated model was then run for a period of 40 years (1977-2016) using as input data the historical rainfall time series and considering a constant phosphorus concentration in the inflow. The model was run for three conditions: i) real reservoir operation, constituting the Reference Scenario; ii) operation including the bed sediment removal when the reservoir was empty (Scenario 1); iii) admitting no phosphorus recycle from the sediment to the water column, which could be accomplished by application of a nutrient-free clay layer, thus, isolating the silted sediment (Scenario 2). With this approach, it was possible to assess the impact of sediment management practices on the eutrophication status of the Tijuquinha reservoir.

Data acquisition and model parameterization

Geometric data of the Tijuquinha reservoir were obtained from a bathymetric survey conducted in April 2016, from which a storage capacity of 5.8×10^5 m³ was estimated, against the 9.7×10^5 m³ original capacity when the dam was built in 1917, representing a reduction due to siltation of the order of 40%. The reservoir shape was well represented by a power-type equation (Equation 11), in which the reservoir volume (V, in m³) may be obtained as a function of the water stage (h, in m) and two parameters: α, representing the reservoir shape, and K, that expresses the reservoir aperture. In the Tijuquinha reservoir, the parameters α and K assume the values of 3 and 257, respectively.

$$V = K \cdot h^{\alpha} \qquad (11)$$

The sedimentation area was also assessed from the data of the bathymetric survey, by comparing the current reservoir bed with that in the year of the dam construction, resulting in an area of 30,000 m² where sediment deposition is concentrated. The average sediment density was measured as 2.58 g/cm³.

The climatic data was obtained from the official Brazilian database, considering 40 years of daily rainfall records in the Baturité gauge (gauge code 00438010 - data from the *"Sistema Nacional de Informações sobre Recursos Hídricos"*, available at www.snirh.gov.br/hidroweb) and average values of monthly potential evaporation in the gauges of Guaramiranga and Fortaleza (data from the *"Normais Climatológicas do Brasil"*, available at www.inmet.gov.br). The Baturité rain gauge (4.33° S; 38.87° W) is located 4 km south from the Tijuquinha reservoir, whereas the Guaramiranga (4.26° S; 38.93° W) and Fortaleza (3.82° S; 38.54° W) evaporation stations are located 8 km and 69 km north of the reservoir, being representative of the top and bottom of the Baturité Massif, respectively, where the catchment is located.

For the water balance computation in the lake, the runoff in the contributing catchment was calculated from the rainfall data with the Curve Number – CN empirical model (USDA 1986), with the CN value estimated as 70 according to the catchment soil and land use. The monthly water withdrawn from the reservoir for supply of the Baturité city was informed by COGERH. The water balance computation in the Tijuquinha reservoir was validated comparing the temporal variability of the reservoir storage with that measured by COGERH in the period from 2009 to 2016 (Figure 2).

The model of phosphorus budget in the water and sediment layers requires information of phosphorus concentrations, as well as phosphorus loads to the reservoir. Such data was estimated from: i) the water quality analyses performed biannually by COGERH from 2009 to 2016 along a vertical profile on a single point of the lake, located close to the dam (deepest point); ii) field campaigns carried out in the present work in June and September 2015, when water samples were collected at different depths along vertical profiles of five locations in both campaigns; iii) field campaigns in June and September 2015, in which sediment was collected with a hand dredger in a single point close to the dam; iv) field campaign in January 2016, when the reservoir was empty, in which surface sediment was collected by shovel in 37 points in the reservoir bed, from which three were also sampled in depth. Total phosphorus in the water was quantified with the ascorbic acid method, according to APHA (1998), whereas phosphorus content in the sediment was analysed by spectrophotometry (Murphy and Riley 1962), which relates its concentration with absorbance through the use of Lambert-Beer Law.

To assess the impact of the removal of nutrient-enriched sediment in the water quality, the temporal dynamics of the trophic state of the reservoir was computed for the simulation of both scenarios, with and without the sediment management practice. The trophic state was defined based on the phosphorus concentrations (Table I), as recommended by Lamparelli (2004) for tropical environments.

The monthly phosphorus input to the lake (W, in mg/month) was computed by the product of the inflows (Q_A, in m³/month) by a constant phosphorus concentration in the runoff (mg/m³). The phosphorus concentration in the runoff was estimated from the highest concentrations measured in the lake in the period 2009-2016 during spillages, assuming that in such occasions, water renewal occurs and the measurements in the lake represent the runoff. By adopting such hypothesis, phosphorus concentration in the runoff was estimated as 340 mg/m³, which is in accordance with measurements carried out by

Table I. Trophic status and the respective total phosphorus (TP) thresholds, according to Lamparelli (2004).

Trophic status	Total phosphorus (mg/L)
Ultraoligotrophic	TP ≤ 0.008
Oligtrophic	0.008 < TP ≤ 0.019
Mesotrophic	0.019 < TP ≤ 0.052
Eutrophic	0.052 < TP ≤ 0.120
Supereutrophic	0.120 < TP ≤ 0.233
Hypereutrophic	TP > 0.233

Peixoto (2014) in eight river sections also in the Baturité Massif, where the average values are within the range of 100 to 380 mg/m³.

For the estimation of the initial phosphorus concentration in the water, the predictive model of Vollenweider (1976) (Equation 12) was used, whereas the phosphorus decay coefficient in the reservoir was calculated as suggested by Salas and Martino (1991) for tropical regions (Equation 13).

$$p_{1i} = \frac{W_y}{V \cdot \left(\frac{1}{\tau_w} + k_s \right)} \tag{12}$$

$$k_s = \frac{2}{\sqrt{\tau_w}} \tag{13}$$

where: p_{1i} is the phosphorus concentration in the water (mg/m³) at the beginning of the simulation period; W_y is the yearly phosphorus load to the lake (mg/year); V is the mean water volume stored in the reservoir (m³); τ_w is the water residence time in the reservoir (year); ks is the phosphorus decay coefficient (1/year).

The initial phosphorus concentration in the sediment was estimate according to Equation 14, proposed by Chapra and Canale (1991).

$$p_{2i} = p_s (1 - \phi) \rho \cdot 10^9 \tag{14}$$

where: p_{2i} is the initial phosphorus concentration in the sediment (mg/m³); p_s is the phosphorus content in the sediment (%); ϕ is the sediment porosity (-); ρ is the sediment density (g/cm³).

Chapra and Canale (1991) found in their work in the Shagawa Lake, in a humid continental climate region, an average total phosphorus content in the sediment in the order of 0.2%. Most values of total phosphorus content in the sediment of the Tijuquinha reservoir range from 0.07% to 0.11%, thus p_s was admitted equal to 0.1%. The measured sediment density accounted for 2.58 g/cm³, the same value found by Chapra and Canale (1991), therefore it was assumed that the porosity of the sediment of the Shagawa Lake (ϕ = 0.9) is representative of the Tijuquinha reservoir as well.

The phosphorus burial velocity (v_b, in m/month) was estimated as proposed by Chapra and Canale (1991) (Equation 15), considering that the phosphorus mass incorporated into the deep sediments can be approximated by the amount retained during the study period (W_{ret}, in mg/month).

$$v_b = \frac{W_{ret}}{A_2 p_2} \tag{15}$$

The phosphorus apparent settling velocity (v_s) was estimated by combining the equation proposed by Chapra and Canale (1991) for total phosphorus budget in the water (Equation 1) and that presented by Vollenweider (1976) (Equation 16), based on a phosphorus decay coefficient in the water (ks), resulting in Equation 17. The parameter ks of the Vollenweider equation has been widely studied and was estimated according to Equation 13.

$$V_1 \frac{dp_1}{dt} = W - Qp_1 - k_s V_1 p_1 \tag{16}$$

$$v_s = \frac{k_s V_1}{A_2} + \frac{v_r p_2}{p_1} \tag{17}$$

To estimate the coefficient of phosphorus recycled mass-transfer (v_r), Chapra and Canale (1991) proposed a model based on the hypolimnetic dissolved oxygen, as this influences the rate of phosphorus transference from the sediment to the water and, thus, may vary across seasons. Nonetheless, reservoirs at low latitudes present low temperature variation among seasons (Dantas et al. 2011), and stratification and destratification occurs in daily steps. In this study, v_r was calibrated to maximize the Nash and Sutcliffe (1970) coefficient (NSE, Equation 18) of the modelled and measured phosphors concentrations in the water. The NSE coefficient ranges from -∞ to 1, and the higher the coefficient, the better the model performance. If NSE is lower than zero, the predictive capacity of the model is lower than simply adopting the mean measured value.

$$NSE = 1 - \frac{\sum_j \left(Y_{meas,j} - Y_{sim,j} \right)^2}{\sum_j \left(Y_{meas,j} - \overline{Y}_{meas} \right)^2} \quad (18)$$

where: $Y_{meas,j}$ and $Y_{sim,j}$ are the measured and simulated values of the variable at time j, respectively; $\overline{Y}$ is the average of the measured values of the variable.

RESULTS AND DISCUSSION

Model parameterization

Estimation/calibration of the parameters of the Chapra and Canale (1991) model (phosphorus apparent settling velocity from the water to the sediment - v_s; coefficient of phosphorus recycled mass-transfer from the sediments to the water - v_r; phosphorus burial velocity to deep sediments - v_b) resulted in the values presented in Table II, which also presents the values found by the above-mentioned authors in their study.

The calibrated value of v_r of 0.00097 m/month is in agreement to that found by Chapra and Canale (1991) for summer conditions in the Shagawa Lake, where v_r was 0.00096 m/month. Considering that, the process of phosphorus recycling from the sediment to the water column is temperature-dependent and that the temperatures are similar in both conditions (Tijuquinha reservoir and Shagawa Lake during summer season), the parameter adopted for Tijuquinha reservoir seems coherent. The phosphorus apparent settling velocity (v_s) of Shagawa Lake (3.52 m/month) is in the upper limit of the range reported by Ruley and Rusch (2004) for temperate lakes. Nevertheless, Salas and Martino (1991) state that the phosphorus decay coefficient of the Vollenweider model (k_s) is twice as high in tropical regions as in temperate climates. The value of 6.45 m/month found for the tropical Tijuquinha reservoir is 1.8 times that of the temperate Shagawa Lake.

Model performance and application for current conditions in the tijuquinha reservoir

Application of the two-layer phosphorus budget model to the Tijuquinha reservoir in the period 2009-2016, with the parameters presented in Table II and considering the real water withdraw from the reservoir, led to the results shown in Figure 4. The model performance was assessed by the indices presented in Table III.

Although the mean absolute error (0.093 mg/L) is in the same order of magnitude of the measured values (average of 0.154 mg/L), the bias close to zero is an indication that there are no systematic errors in the simulation, i.e. the positive errors are well compensated by the negative ones. Figure 5 presents the relationship of phosphorus concentration in the reservoir simulated with the water-sediment interaction model versus the measured data.

Measured phosphorus concentration in the water show relatively high dispersion (Figures

Table II. Parameters of the Chapra & Canale (1991) model for tropical (Tijuquinha) and temperate (Shagawa) lakes.

Parameter	TROPICAL Tijuquinha reservoir	TEMPERATE Shagawa Lake
	(this study)	(Chapra & Canale 1991)
v_s (m/month)	6.45	3.52
v_r (m/month)	0.00097	0.00096 (summer)
v_b (m/month)	0.00256	0.00041

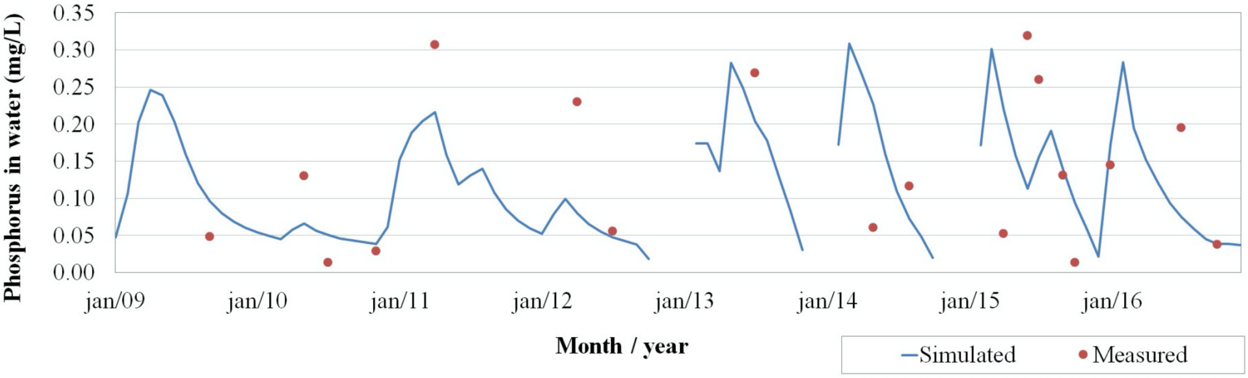

Figure 4. Measured and simulated values of phosphorus concentration in the water of the Tijuquinha reservoir.

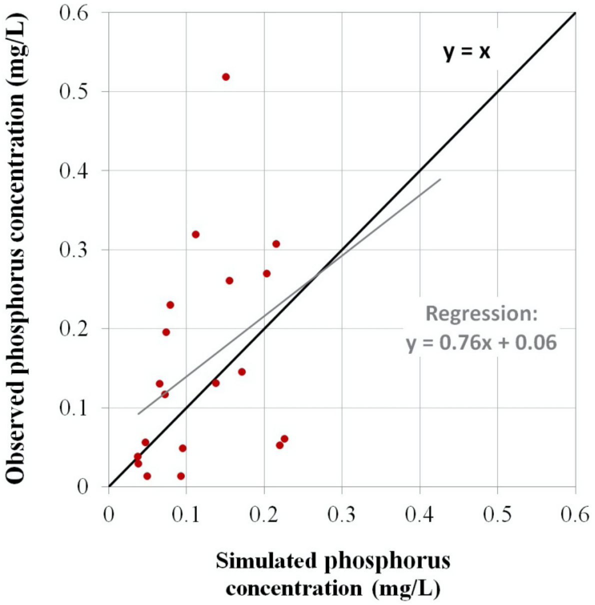

Figure 5. Relationship of phosphorus concentration in the reservoir simulated with the water-sediment interaction model versus the measured data.

5 and 6a), with the simulated values being less dispersed (Figure 5): the full range of simulated values is within the range 1st to 3rd quartile of measured ones (Figure 6a).

Uncertainties on the phosphorus content estimations in this study are not negligible, although Seo and Canale (1996) highlight important features of the Chapra and Canale (1991): i) parsimoniousness, as it depends on three coefficients whereas five of the eight models tested by the above mentioned authors present 5 to 21 coefficients; ii) considers the phosphorus exchange mechanism in the water and sediment layers, as well as phosphorus burial; iii) assumes that the release rate is a function of phosphorus concentration, resulting in seasonally variable sediment release rates.

The main sources of uncertainty in this study seem to originate from the low temporal and spatial distribution of phosphorus measurements, as only 19 campaigns were conducted in the Tijuquinha reservoir and water sampling was point wise; which may not represent the spatial variability of the phosphorus concentrations found by us during field surveys. Seo and Canale (1996) recommend in-lake measurements of settling and sediment release fluxes to reduce model uncertainty.

Additionally, the two-layers phosphorus budget model proposed by Chapra and Canale (1991) and adapted in this study to tropical conditions does not consider the sediment and phosphorus resuspension that may occur in the onset of the rainy season, when water inflows reach the empty reservoir. Furthermore, Hart and Harding (2015) argue that bioturbation by fish may impact phosphorus release from bottom sediments, depending on fish stock abundance and lake eutrophic status. Such features, in addition to temperature differences among seasons, may produce variations of the

Table III. **Error measures and statistical indices for the simulation of the Tijuquinha reservoir using the real water withdraw (RWW) and an average water withdraw (AWW), and the respective reference values.**

Index	RWW	AWW	Best value	Worts value
Bias	-0.035	-0.062	0	± ∞
Mean Absolut Error	0.093	0.113	0	∞
Root Mean Square Error	0.13	0.15	0	∞
Standard deviations Ratio	0.48	0.65	1	0 ou ∞
Deviations Absolute Mean Errors	0.093	0.102	0	∞
Deviations Root Mean Square Error	0.12	0.14	0	∞
Willmott's Index (d)	0.53	0.51	1	0
Pearson's Correlation (r)	0.37	0.22	1	0

phosphorus setting velocity (v_s) and recycling (v_r) along the year, which was not considered in this study and may represent an additional source of uncertainty in the simulations.

Since the water withdraw from the Tijuquinha reservoir has been monitored by COGERH only from 2009, for the longer-period simulations of the sediment management practices, a constant withdraw of 50 L/s was considered, which is compatible with the average observed in the period 2009-2016. The model was run again for that same period in order to assess if there is any significant impact on its performance (Table III).

When compared to the simulation with the real water withdraw from the Tijuquinha reservoir, adoption of a fixed (average) withdraw does not degrade the results significantly (Table III). From box diagrams for the months in which measured phosphorus concentration are available (Figure 6a), one can observe that adoption of a fixed water withdraw increases the range of simulated phosphorus concentration in the water, mostly by reducing the lower values, represented in the graph by the 1st quartile. The median, 3rd quartile and maximum values of simulated phosphorus concentrations are not impacted by the change in the input data.

For all the months in the simulated 2009-2016 period (Figure 6b), the range of phosphorus content in the water is higher for the simulation with the real water withdraw from the Tijuquinha reservoir than for the simulation with constant 50 L/s withdraw.

The phosphorus content in the sediment for the simulation with the real water withdraw from the Tijuquinha reservoir varied from 160 to 310 mg/L, whereas adoption of a constant water withdrawal led to phosphorus concentrations slightly higher in the sediment, within the range of 190 to 320 mg/L (Figure 7).

Replacing the information of real water withdraw from the Tijuquinha reservoir to an average constant value results in impacts of the water balance in the lake and the phosphorus fluxes in the water-sediment system, with relatively lower simulated phosphorus content in the water and higher concentrations in the sediment. Despite the differences, Nash and Sutcliffe coefficient – NSE for simulated against measured phosphorus concentration in the water reaches 0.2 for both simulations, indicating an overall similar performance of the model.

Since water withdraw measurements from the reservoir initiated in 2009, the long-run

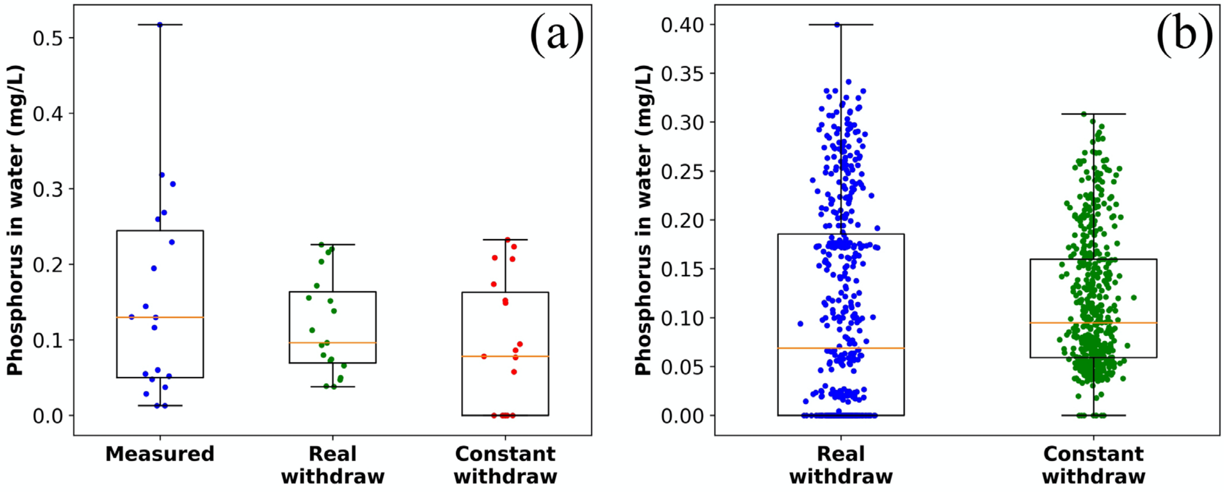

Figure 6. Box diagrams of phosphorus concentration in the water for the period 2009-2016, obtained from the simulations with the real and constant water withdraws from the reservoir: **a)** measured values and the respective (same months) simulated values; **b)** simulated values for all months in the study period.

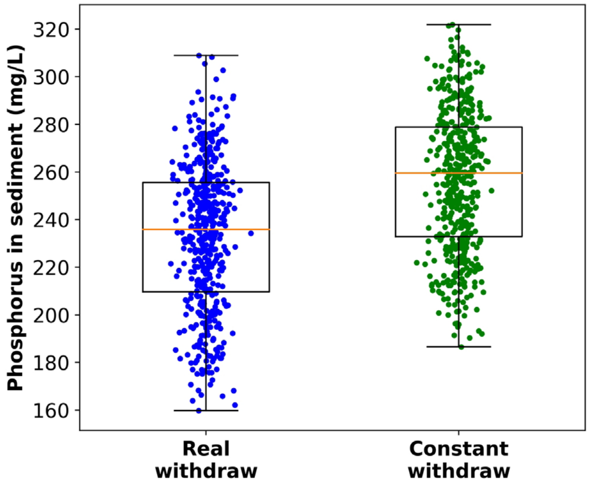

Figure 7. Box diagrams of phosphorus concentrations in the sediment for the period 2009-2016, obtained from the simulations with the real and constant water withdraws from the reservoir.

model application during a 40-years period (1977-2016) was based on the constant 50 L/s water withdraw, representative of the period 2009-2016.

Table IV indicates the percentage of time in which the Tijuquinha reservoir reaches the different trophic states in the simulation period 1977-2016. The temporal phosphorus dynamics in the water-sediment system within the simulated period is illustrated in Figure 8.

During most of the simulated period (56% of the time) the Tijuquinha reservoir presents high trophic state (eutrophic, supereutrophic or hypereutrophic), with more than 40% in supereutrophic and hypereutrophic status. During another 36% of the time, the reservoir remains completely empty, i.e., the Tijuquinha reservoir reaches lower trophic states (mesotrophic, oligotrophic or ultraoligotrophic) in only 8% of the time.

Tropical reservoirs under dry conditions are more prone to eutrophication than those in humid environments, since nutrient accumulation in the formers is favoured by hydrological features such as low and highly variable inflows as well as high evaporation rates (Wiegand et al. 2016). In the State of Ceará, where Tijuquinha is located, high trophic states are observed particularly during droughts: for instance, all strategic reservoirs in the Banabuiú basin (19,800 km² in the central portion of the state) had volumes higher than 80% of their storage capacities after the wet period of the year

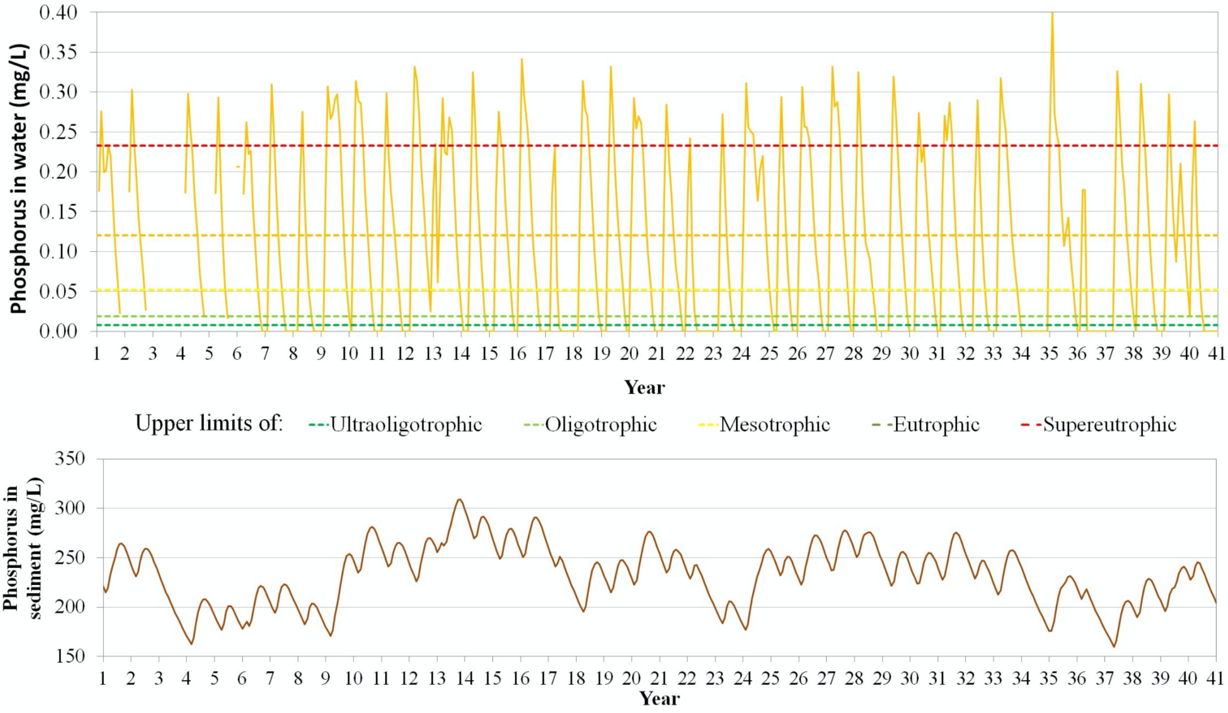

Figure 8. Results of the water-sediment interaction model for the Tijuquinha reservoir adopting a constant mean water withdraw of 50 L/s.

2009, and 55% presented high eutrophication level (eutrophic or hypereutrophic). In 2016, five years after the onset of a long-lasting drought, only 17% of the reservoirs stored more than 80% of their capacities, and all presented high eutrophication level (Abreu 2018).

A strong effect of the intense hydrological variability over the phosphorus content in the water and sediment can be depicted, and a pattern is observed in which three stages can be distinguished (Figure 9).

Stage 1 is characteristic of the rainy season, in which there are large water volumes input to the reservoir, carrying high phosphorus load. In this stage, both the water and the sediment concentrations increase gradually.

In Stage 2, in which the lake is nearly full but there is no inflow at the end of the rainy season, the phosphorus concentration in the water decreases and the concentration in the sediment increases over two or three months. This stage is characterized by the phosphorus transference from the water to the sediment, with the sedimented phosphorus surpassing the amounts fixed and resuspended back to the water column.

Table IV. Percentage of time according to the simulated trophic state of the Tijuquinha reservoir.

Trophic state	% of total time	% of time for non-zero volumes
Empty reservoir	35.6	0
Ultraoligotrophic	0.2	0.3
Oligotrophic	1.8	2.8
Mesotrophic	6.5	10.1
Eutrophic	14.6	22.7
Supereutrophic	24.2	37.6
Hypereutrophic	17.1	26.5

Finally, Stage 3 occurs when the reservoir is empty and, therefore, there is no phosphors

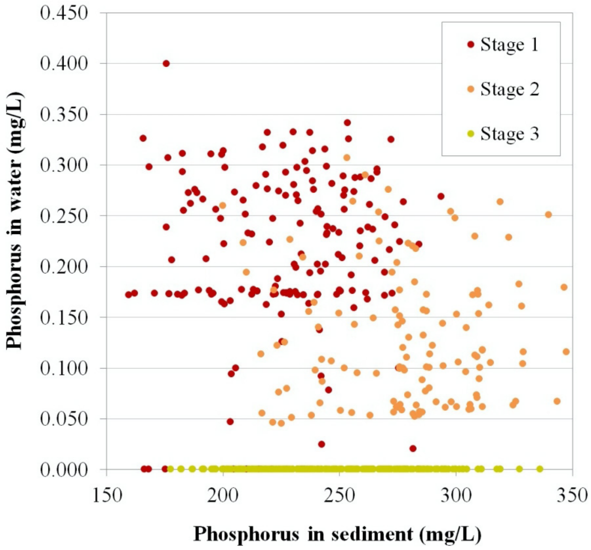

Figure 9. Simulated phosphorus content in water versus sediment in the Tijuquinha reservoir.

in the water (indicated as "zeros" in Figure 9 for visualization purpose). In such situations, the phosphorus concentration in the sediment decreases during the dry season as consequence of the fixation in the lower sediment layers.

It is well recognized that natural lakes and dam reservoirs retain nutrients, and Maavara et al. (2015) project that by 2030, about 17% of the global river total phosphorus load will be sequestered in reservoir sediments. Nonetheless, Chowdhury and Bakri (2006) argue that bottom sediment acts both as source and sink for phosphorous influenced, for instance, by temperature. In their experimental study to quantify nutrient flux at the sediment-water interface in a temperate reservoir in Australia, those authors observed molecular diffusion of phosphorus from sediment to the water during summer. In this study, the temporal dynamics seem to be dominated by the hydrological conditions, i.e. reservoir filling and emptying conditions.

Simulation of the impact of sediment management on the water quality

Impact of the sediment management on the water quality of the Tijuquinha reservoir was assessed by:

- Scenario 1: simulating annual (in December, when the reservoir is usually empty) sediment removal from the reservoir bed, to be used as fertilizer by farmers adopting the practice of sediment reuse. In this simulation, phosphorus content of the remaining layer after sediment removal was considered the same as the average observed in the soils of the catchment;
- Scenario 2: considering no return of phosphorus from the sediment to the water column, due to application of a nutrient-free clay layer over the bed sediment, for instance. Scenario 2 allowed assessment of the amount of phosphorus that originates on the sediment and contributes to increasing the trophic state of the reservoir.

The general results of the simulations of the Reference Scenario (no sediment management), as well as Scenarios 1 (annual sediment removal) and 2 (no phosphorus return from the sediment to the water) are presented on Table V, which indicates the percentage of time according to the simulated trophic state of the Tijuquinha reservoir.

For the period in which there is some water in the reservoir, i.e. it is not empty, Tijuquinha reservoir presents acceptable trophic state (considered as mesotrophic or lower, in this study) in 13% of the time. Adoption of sediment management practices increase this permanence at better trophic states to 23% and 24% of the time for Scenarios 1 and 2, respectively. If the entire simulation period is considered, including the time in which the reservoir is empty, Tijuquinha's trophic state is

Table V. **Percentage of time according to the simulated trophic state of the Tijuquinha reservoir considering no sediment management (Reference Scenario), annual sediment removal (Scenario 1) and no return of the phosphorus from the sediment to the water (Scenario 2).**

Trophic state	% of total time			% of time for non-zero volumes		
	No sediment management	Scenario 1	Scenario 2	No sediment management	Scenario 1	Scenario 2
Empty reservoir	35.6	35.6	35.6	0	0	0
Ultraoligotrophic	0.2	3.1	7.1	0.3	4.8	11.1
Oligtrophic	1.8	4.3	2.5	2.8	6.7	3.8
Mesotrophic	6.5	7.5	6.1	10.1	11.7	9.5
Eutrophic	14.6	9.6	9.4	22.7	14.9	14.6
Supereutrophic	24.2	24.2	23.8	37.6	37.6	37.0
Hypereutrophic	17.1	15.7	15.5	26.5	24.3	24.0

acceptable during 9%, 15% and 16% of the time for the Reference Scenario, Scenario 1 and 2, respectively.

According to the simulations, sediment management practices produce minor improvement in the water quality of the Tijuquinha reservoir, changing the trophic state from poor (eutrophic or higher) to acceptable (mesotrophic or lower) in 10% and 11% of the time in which the reservoir is not empty, for Scenarios 1 and 2, respectively. Nonetheless, considering that Tijuquinha presents high trophic state in 87% of the time in which it is not empty, any water quality improvement is desired.

Furthermore, it is expected that phosphorus retention in reservoirs rise substantially in the next decades, particularly in developing countries where the increasing need for water and energy has resulted in the construction of thousands of dams (Maavara et al. 2015). Particularly in North America and Europe, recognition that nutrient enrichment impacts the ecological function of catchments and the water supply systems has led to reductions in phosphorus loading to lakes. However, broader water- and environmental-quality measures are still needed (Conley et al. 2009). The sediment reuse meets such demands, presenting the ecological advantage of recycling what is often considered as a waste material and representing a low-cost alternative to the management and disposal of dredged sediment (Bondi et al. 2016). Other practices to reduce phosphorus content in lakes have been proposed, as the biomanipulation by fish removal (Hart and Harding 2015), but it is extensively stated that reduction of phosphorus loads to superficial water bodies is more efficient on eutrophication control (Conley et al. 2009, Hart and Harding 2015).

Regarding the impact of impact of sediment management in the phosphorus content in the reservoir bed, sediment removal annually (Scenario 1) produce intense reduction of the phosphorus accumulation in the sediment layer: while phosphorus concentration may reach up to 300 mg/L with average value of 233 mg/L in the Reference Scenario, in Scenario 1 the maximum and mean values are 150 mg/L and 78 mg/L, respectively. With the phosphorus recycling to the water (v_r) set to zero (Scenario 2), the bed sediment would accumulate 11% more phosphorus than in the Reference Scenario.

Therefore, frequent sediment management may also impact the willingness of farmers to adopt the sediment reuse practice.

CONCLUSIONS

A two-layer phosphorus budget model was adapted to tropical conditions and used to simulate the effect of sediment management on the phosphorus content in the water and sediment of the Tijuquinha reservoir (roughly 6 x 10^5 m³ storage capacity), located in Ceará, Brazil. Despite the model simplifying hypotheses (for example, complete mixing in the lake and disregard of sediment resuspension due to turbulence and fish bioturbation) and uncertainties in the measured phosphorus content (relatively low number of measurements), the model was able to adequately simulate the phosphorus dynamics in the reservoir, representing well the range of measured values.

Model application for a 40-years period (1977-2016) under current operation conditions, i.e. no sediment management practices, indicated that the Tijuquinha reservoir remains empty during 36% of the time, reaching high trophic state (eutrophic or higher) in 56% of the time. The simulated trophic state has reached lower levels (mesotrophic or lower) in 8% of the time, only.

The model was run for the same period adopting sediment management practices: Scenario 1, in which annual sediment removal was considered; Scenario 2, admitting no return of phosphorus from the sediment to the water column, for instance by application of a nutrient-free clay layer. For the period in which there is some water in the reservoir, i.e. the reservoir is not empty, the sediment management practices improved the water quality, changing the trophic state from high to mesotrophic or lower, in 10% and 11% of the time for Scenarios 1 and 2, respectively.

The simulations indicate that sediment management practices produce minor improvement in the water quality of the Tijuquinha reservoir, but considering that it presents high trophic state in 87% of the time when not empty, any water quality improvement is desired. In addition, reuse of sediment as nutrient source in agriculture reduces the application of chemical fertilizers, thus, avoiding introduction of exogenous nutrient from the catchment-reservoir system and contributing to the overall water quality.

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CAMILA C.S LIRA[1]
https://orcid.org/0000-0002-4882-5576

PEDRO H.A. MEDEIROS[2]
https://orcid.org/0000-0002-4879-3148

IRAN E. LIMA NETO[3]
https://orcid.org/0000-0001-8612-5848

[1]Universidade Federal do Ceará, Departamento de Engenharia
Agrícola, Centro de Ciências Agrárias, Campus do Pici, Av.
Mister Hull, s/n, Bloco 804, 60455-760 Fortaleza, CE, Brazil

[2]Instituto Federal de Educação, Ciência e Tecnologia
do Ceará, Campus Maracanaú, Av. Parque Central,
s/n, 61939-140 Maracanaú, CE, Brazil

[3]Universidade Federal do Ceará, Departamento
de Engenharia Hidráulica e Ambiental, Centro de
Tecnologia, Campus do Pici, Av. Mister Hull s/n, Bloco
713, 1º andar, 60451-970 Fortaleza, CE, Brazil

Correspondence to: **Camila Cristina Souza Lira**
E-mail: eng.camilalira@gmail.com

Author contributions

Camila Lira conducted the study by collecting data in the field, performing the computational simulations and producing the results. Pedro Medeiros idealized and supervised the research, contributed to the discussion and text review. Iran Lima Neto co-supervied the research and contributed to the discussion and text review.