Water SA 48(3) 278–285 / Jul 2022
https://doi.org/10.17159/wsa/2022.v48.i3.3893

Research paper

Seasonal and interannual variability of residence time and total phosphorus in a small hypereutrophic lake in the Brazilian northeast

Sofia MG Rocha[1], **Maria de JD Rocha**[1], **Germário M Araújo**[1], **Helena Becker**[2] **and Iran E Lima Neto**[1]

[1]Department of Hydraulic and Environmental Engineering, Federal University of Ceará – UFC, Fortaleza, Brazil
[2]Department of Chemistry, Federal University of Ceará – UFC, Fortaleza, Brazil

This study evaluates the residence time (RT) and total phosphorus (TP) in a small hypereutrophic lake in the city of Fortaleza, Brazil. The results indicate that RT predicted by a complete-mix model is very similar (R^2 = 0.83) to that simulated with a 2-D hydrodynamic model (CE-QUAL-W2). Simple power-laws were fitted to describe RT and TP concentration at the lake inlet as functions of lake inflow, yielding correlations of R^2 = 0.84 and 0.70, respectively. The combination of these correlations with a complete-mix approach provided a comprehensive model that predicted TP values measured at the lake outlet reasonably well (R^2 = 0.60). In addition, a direct empirical correlation between simulated TP concentration and precipitation was also obtained. The simulations indicate a nearly periodic behaviour of RT and TP, with the seasonal variations being much higher than the interannual ones. Finally, an application of the model showed that a reduction of 99% of the input TP load was required to reach 100% compliance with the required water quality standards; this could be achieved by connecting the residences to the sewage network. The methodology proposed in this research can be easily applied to other lakes in the Brazilian northeast and extended to other tropical regions around the globe.

CORRESPONDENCE
Sofia MG Rocha

EMAIL
sofiamidauar@gmail.com

DATES
Received: 30 March 2021
Accepted: 27 June 2022

KEYWORDS
CE-QUAL-W2
complete-mixing
eutrophication
hydrodynamics
water quality modeling

INTRODUCTION

Lake eutrophication is a global issue closely associated with total phosphorus (TP) loadings (Chapra, 2008). In many tropical regions, such as Brazil, several water bodies are already eutrophic or hypereutrophic due to high TP loadings (Mekonnen and Hoekstra, 2018; Namugize and Jewitt, 2018; Lira et al., 2020; Moura et al., 2020; Rocha and Lima Neto, 2021, 2022). Because of deficient sanitation facilities, this problem becomes even more severe in lakes and reservoirs located in low-income urban areas, where TP concentration far exceeds the mandatory water quality standards (Pacheco and Lima Neto, 2017; Toné et al., 2018; Araújo et al., 2019).

Classical studies on TP modelling in lakes have been reported by Vollenweider (1968) and Chapra (2008). Since then, assessment of catchment hydrology, lake hydrodynamics and TP values have been improved on by several researchers with a variety of modelling approaches (Chapra and Canale, 1991; Salas and Martino, 1991; Shen et al., 2002; Chapra et al., 2016; Xu et al., 2017; Cullis et al., 2018; Araújo et al., 2019; Oliveira et al., 2020). In this context, input loads of TP from the catchment (W) and hydraulic residence time (RT) are fundamental – from the simplest classical zero-dimensional TP balance model of Vollenweider (1968) to more complex multidimensional ones.

The quantification of the TP input loads (W) from the catchment is necessary to assess the seasonal and interannual variation of TP concentration in rivers (Rattan et al., 2016; Janssen et al., 2019; Raulino et al., 2021, Wiegand et al., 2021; Lima Neto et al., 2022). This has been done by coupling hydrological models to river water quality models or simply by adjusting empirical correlations relating flow rate to TP concentration (Bowes et al., 2008–2015; Bieroza and Heathwaite, 2015; Chen et al., 2015; Mockler et al., 2017; Zhang et al., 2020). However, there is no single model or general correlation to describe the relationships between flow rate or precipitation and TP loads from the catchment, since much of the variation in TP load with precipitation or flow rate depends on the climatic conditions, catchment characteristics, and anthropogenic activities.

On the other hand, water residence time (RT) plays an important role in the lake hydrodynamics and water quality (Ambrosetti et al., 2003; Jones and Elliott, 2007; Wan et al., 2013; Mahanty et al., 2016; Laspidou et al., 2017; Tong et al., 2019). RT is commonly estimated assuming the complete-mix approach, by simple division of lake volume by its inflow (Rueda et al., 2006; Pilotti et al., 2014). Nevertheless, RT is an intricate variable influenced by and depending on many parameters such as lake morphometry, flow rate and stratification (Castellano et al., 2010; Pilotti et al., 2014; Soares et al., 2019), and may accordingly require more detailed studies using multidimensional model simulations (Messager et al., 2016; Kim et al., 2019).

The objective of this research was to evaluate the seasonal and interannual variability of RT and TP in a small hypereutrophic lake located in the northeastern Brazilian city of Fortaleza. Its main goals were: (i) to compare RT estimates based on a two-dimensional (2-D) hydrodynamic model and the complete-mix approach; (ii) to obtain innovative relationships to describe RT and W as a function of the lake inflow; and (iii) to provide a comprehensive model to predict the seasonal and interannual variations of RT and TP concentration in the study lake. Additionally, an empirical correlation between TP and precipitation is also proposed. As an application of the results, different scenarios of W reduction are presented to analyse compliance with water quality standards. The limitation of this study is that it relies on the empirical (site-specific) nature of the proposed correlations, which may not be directly applied to other systems, but it instead proposes a methodology that can be applied for other systems.

METHODS

Study site

The study was carried out in Lake Santo Anastácio (LSA), which is located in the city of Fortaleza, in the northeastern Brazilian state of Ceará (Fig. 1). LSA is a hypereutrophic lake (Pacheco and Lima Neto, 2017) with an average surface area of about 16 ha and a maximum depth of about 5 m. Water temperature in the lake is approximately 30°C throughout the year. Annual precipitation in the area ranges from 1 000 to 2 500 mm, with two well-defined seasons: the wet season, from February to May, when most rainfall occurs, and the dry season from June to January. LSA is fed from a catchment area of about 4 km^2 drained by a 2.5 km long, 5.0 m wide channel The water is discharged from LSA through a 2.0 m wide Creager spillway.

Part of the LSA catchment area is served by a sewerage network, but most residences are not connected to the system. The lake also receives large inputs of untreated sewage from informal settlements surrounding the drainage channel. More details of the study area can be found in Fraga et al. (2020). Table 1 presents data from water quality measurements in LSA, where the ecological conditions of the lake are shown (Pacheco and Lima Neto, 2017; Araújo et al., 2019; Fraga et al., 2020; Mesquita et al., 2020).

Field study and data analysis

The field surveys were conducted during the dry and wet seasons of 2018 and 2019. Water depths at the end of the drainage channel and at the Creager spillway, measured with a ruler, were used to calculate lake inflows and volumes with the following depth–discharge and depth–volume curves adjusted to the data of Araújo and Lima Neto (2018):

$$Q_{in} = 11.22\, h_c^{3.69} \quad (R^2 = 0.84) \tag{1}$$

$$V = 13\,045\, h_s^2 + 27\,357\, h_s \quad (R^2 = 0.92) \tag{2}$$

where Q_{in} (m^3/s) is the lake inflow, h_c (m) is the water depth at the lake inlet (end of the drainage channel), V (m^3) is the lake volume, and h_s (m) is the water depth at the lake outlet (spillway).

Water samples were collected at the lake inlet and outlet at mid-depth using Van Dorn bottles for rapid analysis at the nearby Environmental Chemistry Lab (LAQA) at the Federal University of Ceará (UFC), where TP concentration was determined following APHA Standard Methods (APHA, 2012). Hydrometeorological parameters (rainfall, evaporation, air temperature, cloud cover, and wind speed and direction) were measured on a daily basis from 2009 to 2019 in a meteorological station located about 1.0 km from the lake outlet.

Hydrodynamic modelling

The 2-D laterally-averaged hydrodynamic model CE-QUAL-W2 (Cole and Wells, 2018) was chosen for this study, as it is well-suited to relativity long and narrow water bodies like LSA, and is largely applied to lakes and reservoirs (Deus et al., 2013; Sadeghian et al., 2018; Terry et al., 2018; Zhang et al., 2018).

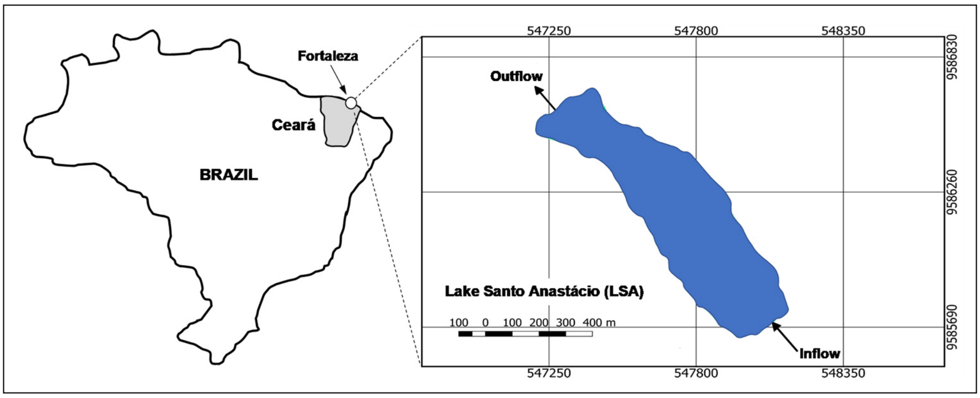

Figure 1. Schematic of Lake Santo Anastácio (LSA), located in the city of Fortaleza, state of Ceará, Brazil

Table 1. Typical ranges of water quality parameters in LSA

Parameter		Year
Total phosphorus (mg/L)	0.4–7.2	2013
	1.53–2.16	2016
Organic phosphorus (mg/L)	0.2–2.1	2013
Orthophosphate (mg/L)	0.1–0.9	2013
Chlorophyll_a (µg/L)	0.3–65.7	2013
	54–76	2016
Total nitrogen (mg/L)	1.58–2.44	2016
Dissolved oxygen (mg/L)	4.3–7.1	2013
Biological oxygen demand (BOD) at outlet (mg/L)	17.1–36.1	2013
Chemical oxygen demand (COD) at outlet (mg/L)	49.3–112.0	2013
Total coliforms (MPN/100 mL)	9 630–97 540	2018
Escherichia coli (MPN/100 mL)	560–1 100	2018

Pacheco et al., 2017; Araújo et al., 2019; Fraga et al., 2020; Mesquita et al., 2020

We used a CE-QUAL-W2 model previously calibrated/validated for LSA (Mesquita et al., 2020). The input data consisted of flow rates, bathymetry and meteorology. To fill the gaps in the times series of flow rate, we used a correlation provided by Mesquita et al. (2020), in which the inflows were calculated as a function of daily precipitation measured at the meteorological station from 2009–2019:

$$Q_{in} = 0.036P + 0.11 \quad (R^2 = 0.93\ p < 0.05, \alpha = 0.05, \text{df} = 2) \quad (3)$$

where P (mm) is the daily precipitation and df is degrees of freedom. The constant of 0.11 m^3/s in Eq. 3 represents the nearly steady-state flow condition resulting from sewage discharge into the urban drainage channel that feeds LSA, while the direct relationship between Q_{in} and P reflects the impermeable nature of the catchment.

The above procedures allowed CE-QUAL-W2 simulations of lake hydrodynamics and residence time (RT) for the entire time series. In the model, RT is also called water age, defined as the mean time that water spends in a particular cell in the 2-D computational grid. An average of all RT grid cell values was made in order to compare 2-D results with those obtained by the complete-mix hypothesis.

Alternatively, residence time was also estimated using a complete-mix approach – by simple division of lake volume by its inflows (see Rueda et al., 2006; Pilotti et al., 2014). As for the CE-QUAL-W2 simulations, gaps in the flow rate times series were filled using Eq. 3. On the other hand, the following correlation obtained from the data available in Araújo and Lima Neto (2018) was used to fill the gaps in the lake volume times series:

$$V = 311\,963 + 128\,495\,Q_{in} \quad (R^2 = 0.96, p < 0.05, \alpha = 0.05, \text{df} = 2) \quad (4)$$

Using the complete-mix approach, Eqs 3 and 4 collectively enable estimates of water residence time for the entire time series:

$$\text{RT} = V/Q_{in} \quad (5)$$

Equation 5 quantifies the lake's flushing rate, which is the time required for the inflow to replace the quantity of water in the reservoir (Chapra, 2008) – a major determinant of water quality in the water body. Shorter RT values imply that water quality is primarily related to inflow, while longer RT values suggest significant effects of surface and bottom inputs along with biological activity (Fischer, 1979).

Total phosphorus modelling

TP modelling in the lake was performed by using a transient complete-mix approach (Vollenweider 1968; Chapra, 2008):

$$\text{TP} = \text{TP}_o \cdot \exp(-\lambda t) + W/(\lambda V) \cdot [1 - \exp(-\lambda t)] \quad (6)$$

In Eq. 6, TP_o and TP (kg/m³) are the initial and final total phosphorus concentrations at the lake outlet, respectively, for each time step t (s); $\lambda(s^{-1}) = k + 1/\text{RT}$, where k (s^{-1}) is the settling loss rate of TP; and W (kg/s) is the TP load at the lake inlet, given by $W = \text{TP}_{in} \cdot Q_{in}$, in which TP_{in} (kg/m³) is the TP concentration at the lake inlet.

We used a settling loss rate (k) of 7.2 x 10^{-7} s^{-1} obtained from Araújo et al. (2019). Moreover, correlations of RT and W as a function of Q_{in} were also adjusted in order to provide, together with Eqs 3–6, a novel, simple and comprehensive model that can be used to investigate the seasonal and interannual variations of TP concentration in the study lake. An empirical correlation between TP and P was also determined, to provide some understanding of the impacts of rainy events on in-lake TP concentrations.

Finally, as an application of the proposed model, different scenarios of W reduction were analysed to study prospective compliance with the National Surface Water Quality Standards (CONAMA 357/2005: Brazilian National Environment Council, 2005).

RESULTS AND DISCUSSION

A CE-QUAL-W2 simulation of water temperature at the surface and bottom of LSA for a year (2015) of typical annual precipitation (1 500mm) was developed (Fig. 2). Differences between top and bottom temperatures were usually lower than 2°C, as expected for shallow water bodies in tropical regions (Lewis, 2000), and confirming the lake's relatively weak stratification. Similar results obtained for other years in the time series corroborated field measurements of the thermal regime in LSA by Lima Neto (2019) and numerical simulations thereof by Mesquita et al. (2020).

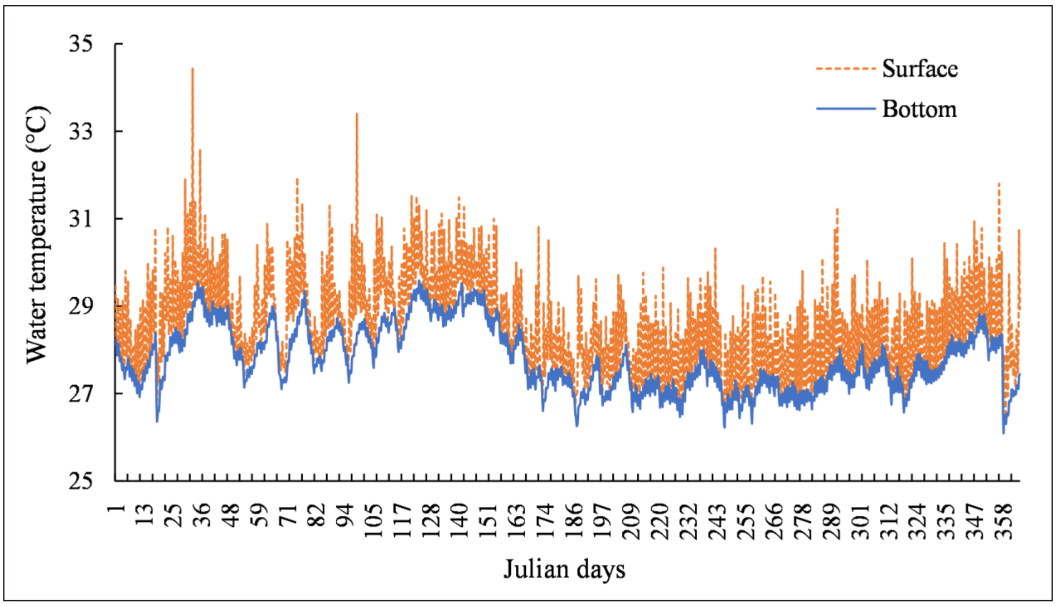

Figure 2. CE-QUAL-W2 simulation of LSA surface and bottom water temperatures for a typical year (2015)

Figure 3 compares the time series of RT predictions from the space-averaged CE-QUAL-W2 and the complete-mix models (Eq. 5) in relation to measured precipitation (P) data. The clear inverse dependence between RT and P that is evident suggests that inflow (Q_{in}), which is directly related to P through Eq. 3, has a predominant influence on the hydrodynamics of LSA. The RT time series predictions of the complete-mix model correlate strongly ($R^2 = 0.83$, $p < 0.05$, $\alpha = 0.05$, df = 2) with those simulated by CE-QUAL-W2, with both models yielding approximately similar average RT values of about 0.7 months. This implies that the complete-mix approach is a reasonable approximation for the lake. In contrast, while annual-averaged RT values obtained from a 1-D hydrodynamic model (DYRESM) and the complete-mix model for a larger seasonally-stratified lake in Spain matched closely, monthly-averaged RT values differed considerably (Rueda et al., 2006). Conversely, Pilotti et al. (2014) found that DYRESM simulations of RT were about twice the RT estimates given by the complete-mix model for a strongly stratified lake in Italy.

In our study, seasonal variations of RT were much more pronounced than interannual ones (Fig. 3), with a roughly 5-fold difference in RT values between dry and wet seasons. This ratio is within the range of 2 to 35-fold reported in the literature for lakes under different climatic and hydrodynamic conditions (Rueda et al., 2006; Jones and Elliott, 2007; Pilotti et al., 2014; Mahanty et al., 2016).

Both RT and TP concentration varied monotonically with inflow Q_{in} (Fig. 4). As already discussed (see Eq. 3 and Fig. 3), P and Q_{in} were the dominant influences on the hydrodynamics of LSA, helping to explain the good fit ($R^2 = 0.84$, $p < 0.05$, $\alpha = 0.05$, df = 2) between RT simulated with CE-QUAL-W2 and the values of Q_{in} in Eq. 7. Consistently, the complete-mix model (Eq. 5) provided a similar curve to the power-law fitted to the CE-QUAL-W2 data. On the other hand, since only part of the study area is covered by a sewerage network, to which several residences are not connected, much raw sewage is discharged into the drainage channel (Araújo and Lima Neto, 2018; Araújo et al., 2019; Fraga et al., 2020). As this suggests a complete dominance of point-source TP input to LSA, simple power-law models such as Eq. 8 ($R^2 = 0.70$, $p < 0.05$, $\alpha = 0.05$, df = 2) adequately describe the relationship between TP concentration and Q_{in} (see Bowes et al., 2008); particularly since the catchment area of the lake is predominantly impermeable, with no complex hysteretic TP pattern observed (see Bieroza and Heathwaite, 2015).

$$RT = 0.14\, Q_{in}^{-0.93} \quad (R^2 = 0.84,\ p < 0.05,\ \alpha = 0.05,\ \mathrm{df} = 2) \tag{7}$$

$$TP_{in} = 0.46\, Q_{in}^{-0.86} \quad (R^2 = 0.70,\ p < 0.05,\ \alpha = 0.05,\ \mathrm{df} = 2) \tag{8}$$

Note that the TP load at the lake inlet is given by $W = TP_{in} \cdot Q_{in}$.

Importantly, total phosphorus concentrations in the drainage channel (TP_{in}) ranged from 0.23 mg/L to 5.71 mg/L, and averaged 2.23 mg/L – values very much higher than the limit of 0.05 mg/L established by the National Surface Water Quality Standards (CONAMA 357/2005: Brazilian National Environment Council, 2005). During low-flow conditions ($Q_{in} \approx 0.11$ m³/s), TP_{in} was of the order of typical concentrations (4.0 mg/L) reported for untreated domestic sewage (Chapra, 2008). This implies that as Q_{in} increases with precipitation (see Eq. 3), sewage becomes diluted and TP_{in} decreases to around 0.5 mg/L, but still remains 10-fold higher than the above mandatory standard.

The combination of Eqs 3–8 provides a simple and comprehensive complete-mix model (Fig. 5) that predicts empirical measurements of total phosphorus at the lake outlet (TP_{out}) reasonably well ($R^2 = 0.60$, p = 0.07, $\alpha = 0.05$, df = 2). The relationship between simulated TP_{out} and measured precipitation is described by the negative exponential regression:

$$TP_{out} = 2.27e^{-0.03P} \quad (R^2 = 0.94,\ p < 0.05,\ \alpha = 0.05,\ \mathrm{df} = 2) \tag{9}$$

This regression also fits the TP_{out} data measured during our study (Fig. 5 – red scatter points) reasonably well ($R^2 = 0.58$, $p = 0.08$, $\alpha = 0.05$, df = 2) – not unexpectedly – since the catchment area of LSA is located in an urban region with deficient sanitation. As TP loads are diluted by rainy events, the relationship described in Eq. 9 offers a potential management tool for LSA and other similar lakes – as its independent parameter (precipitation) is such an easily and widely measured parameter.

The values of TP_{out} confirm that the lake is hypereutrophic (Pacheco and Lima Neto, 2017), with its phosphorus concentration being consistently higher than the limit of 0.03 mg/L established by the National Surface Water Quality Standards (CONAMA 357/2005: Brazilian National Environment Council, 2005). In fact, the average TP concentration (1.68 mg/L) is about 56-fold larger than the required standard. The nearly periodic behaviour of the simulated time series implies that the dry weather TP load at the lake inflow (W) – mostly attributable to sewage discharge – is approximately constant, with the values of both TP_{in} and TP_{out} being essentially controlled by precipitation (or flow rate). As already noted for RT (see Fig. 3), the seasonal variations of TP_{out} are much more important than the interannual ones, with a roughly 4-fold dry to wet season TP ratio. In contrast, using CE-QUAL-W2, segmented complete-mix models or generalized linear models (GLMs), Deus et al. (2013), Chapra et al. (2016), Kim et al. (2019) and Oliveira et al. (2020) found higher seasonal and interannual variations of TP in large stratified lakes. The difference (compared to the present study) may be attributed to the complexity of their catchments, lake hydrodynamics and anthropogenic effects.

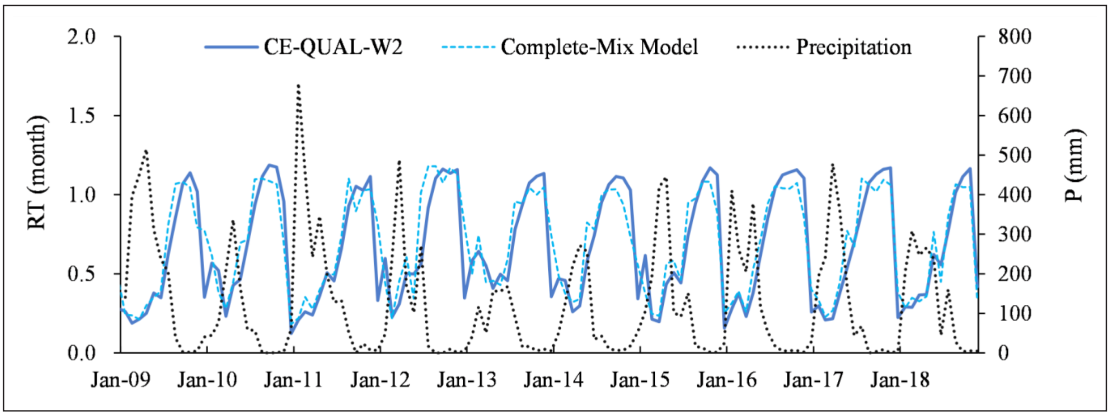

Figure 3. Residence time (RT) simulations by 'complete-mix' and CE-QUAL-W2 models in relation to measured precipitation (P) from 2009 to 2018

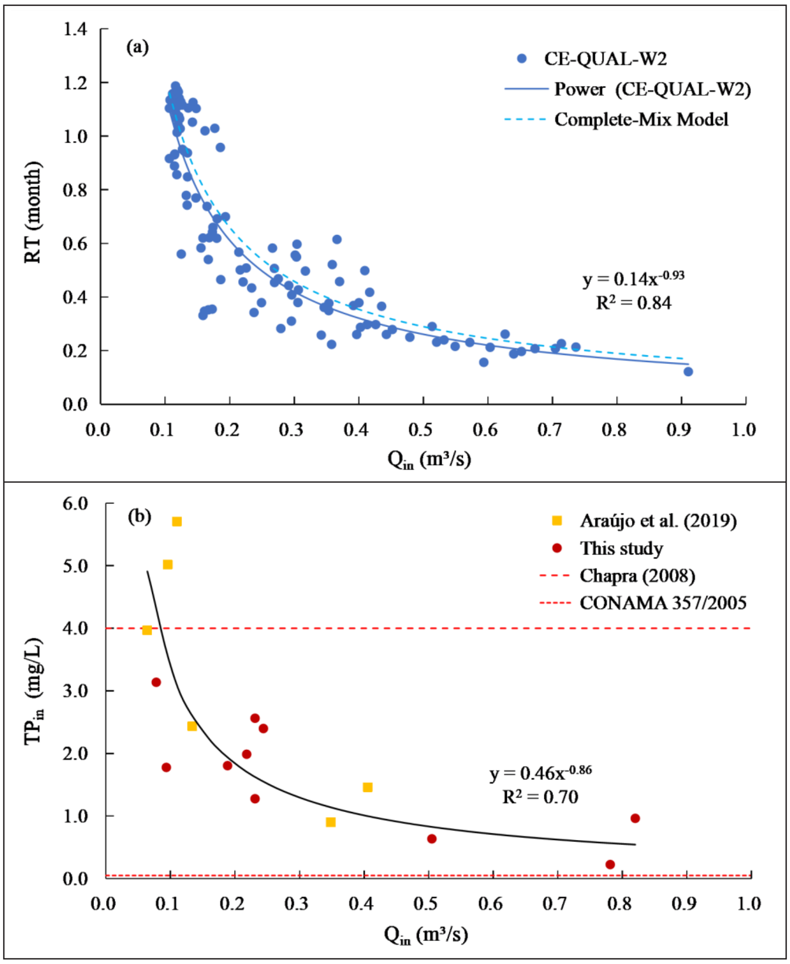

Figure 4. Relationships of residence time (a) and total phosphorus concentration at the lake inlet (b) as functions of the inflow

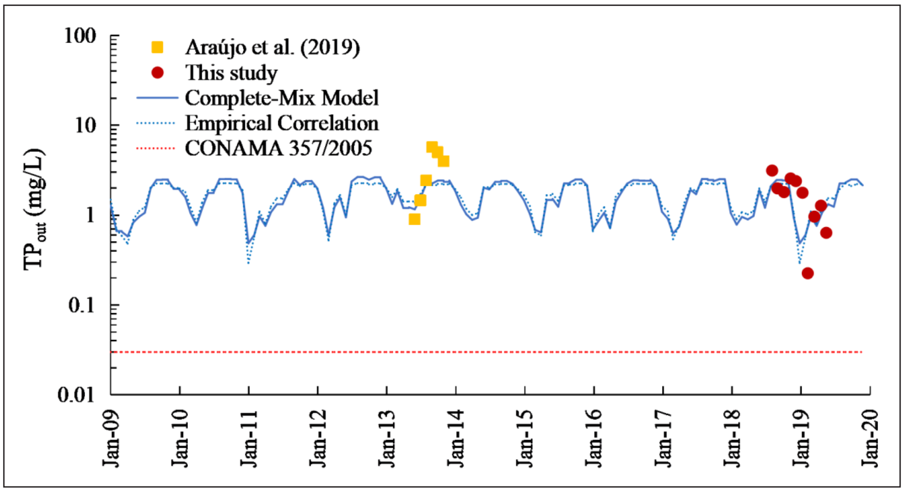

Figure 5. Validation of the complete-mix model (Eqs. 3–8) and its empirical correlation (Eq. 9) with respect to field data of total phosphorus concentration at the lake outlet

As an application of the results obtained in this study, different TP load (W) reduction scenarios were investigated by applying the comprehensive complete-mix model (Eqs. 3–8) to the 10-year time series (Fig. 7). The simulations indicate that in order to meet 100% compliance with the National Surface Water Quality Standards (CONAMA 357/2005: Brazilian National Environment Council, 2005), the actual TP input load to LSA (W) would need to be reduced by 99%. This would require all residences in the catchment to be connected to the local sewerage network and/or their sewage outflows to be redirected to other sewage systems.

Finally, our results indicated that simple power-law equations together with a complete-mix approach are sufficient to describe RT and TP in LSA. Such results are of the utmost importance, as the Brazilian northeast presents thousands of small reservoirs with similar characteristics to LSA (Lima Neto et al., 2011; Rabelo et al., 2021; Wiegand et al., 2021). Therefore, simple methodologies such as the one proposed in our study are needed to couple hydrologic and TP modelling at the basin scale and improve water resources management.

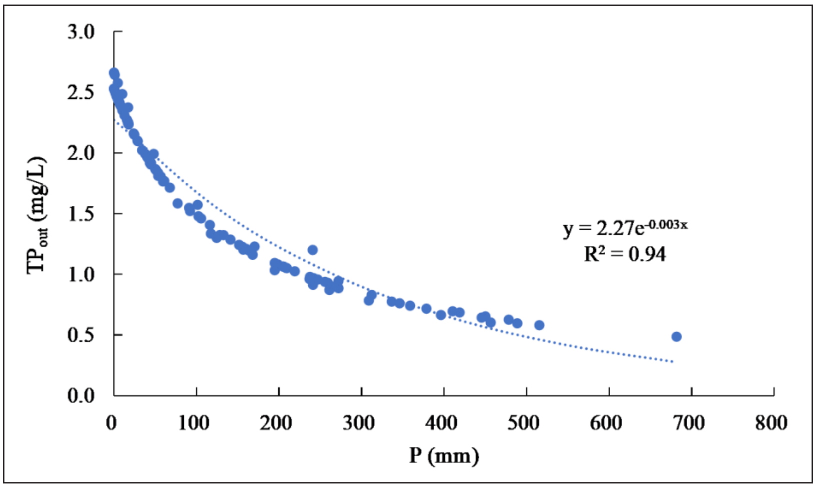

Figure 6. Simulated total phosphorus concentration as a function of measured precipitation and the exponential regression curve fitted to the plotted data

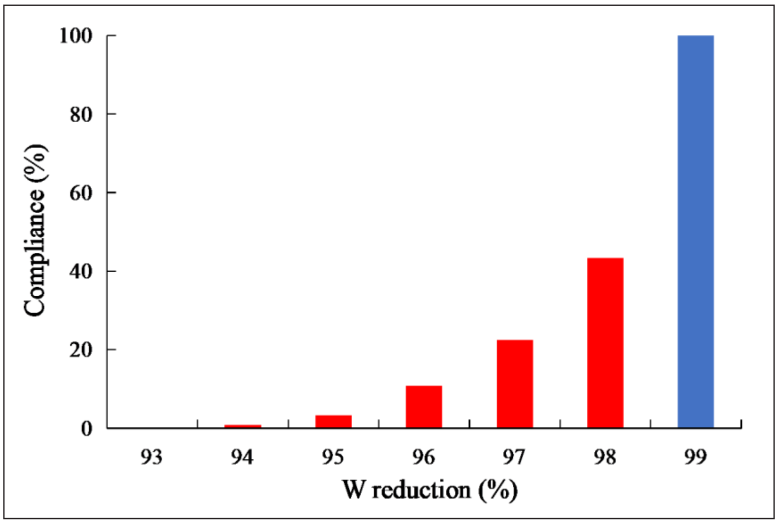

Figure 7. Scenarios of TP load (W) reduction for compliance with the National Surface Water Quality Standards (CONAMA 357/2005: Brazilian National Environment Council, 2005)

CONCLUSIONS

This paper investigated the seasonal and interannual variability of residence time (RT) and total phosphorus (TP) in a small hypereutrophic lake in Fortaleza, Brazil. The field studies and numerical simulations revealed that the lake behaved approximately as a well-mixed system, as the RT time series predicted by a complete-mix model was very similar to that simulated with CE-QUAL-W2. This indicates that simpler models can provide reliable results, depending on the complexity of the studied system. Furthermore, the seasonal variations of RT were significantly higher than the interannual ones. Because of the impermeable nature of the catchment area, precipitation and flow rate were the dominant influences on the lake's hydrodynamics, allowing the fitting of simple power-law equations to predict RT and TP concentration at the lake inlet to lake inflow. The combination of these equations with a complete-mix approach provided a comprehensive model that was able to predict the field data of TP at the lake outlet. Moreover, a simple relationship between simulated TP concentration and precipitation was also obtained, which is a potential management tool. The simulations indicated a nearly periodic behaviour of TP concentration in the lake, with the seasonal variations again being significantly higher than interannual ones. An application of the proposed model suggested that only a TP load reduction of 99% would comply with the national water quality standards. This would necessitate residences being connected to the local and/or other sewage networks. This result is important, as the Brazilian northeast and other tropical regions around the globe present thousands of small ponds, lakes and reservoirs with similar characteristics to LSA, where urgent sanitation measures must be taken to improve water quality. Finally, simple methodologies such as that proposed here are important to couple hydrologic and TP modelling at the basin scale and improve water resources management.

ACKNOWLEDGEMENTS

The present study was supported through the Coordination for the Improvement of Higher Education Personnel – CAPES [Research Grant PROEX 20/2016] and the Ceará State Research Foundation – FUNCAP [Research Grant PNE-0112-00042.01.00/16].

AUTHOR CONTRIBUTIONS

First author – data collection, data analysis, interpretation of results, writing of the initial draft; second author – interpretation of results, data analysis; third author – data collection and field work; fourth author – data collection and fieldwork; fifth author – project management, conceptualisation and methodology of the study, data collection, data analysis, interpretation of results.

ORCID

Sofia MG Rocha
https://orcid.org/0000-0001-5296-5355

REFERENCES

AMBROSETTI W, BARBANTI L and SALA N (2002) Residence time and physical processes in lakes. *J. Limnol.* **62** (S1). https://doi.org/10.4081/jlimnol.2003.s1.1

APHA (American Public Health Association) (2012) Clesceri LS, Rice E, Franson MAH (eds). *Standard Methods for the Examination of Water and Wastewater* (23rd edn). APHA, Washington, DC. 1 504 pp.

ARAÚJO GM and LIMA NETO IE (2018) Removal of organic matter in stormwater ponds: a plug-flow model generalisation from waste stabilisation ponds to shallow rivers. *Urban Water J.* **15** (9) 918–924. https://doi.org/10.1080/1573062x.2019.1581231

ARAÚJO GM, LIMA NETO IE and BECKER H (2019) Phosphorus dynamics in a highly polluted urban drainage channel shallow reservoir system in the Brazilian semiarid. *An. Acad. Bras. Cienc.* **91** (3) 1–8. https://doi.org/10.1590/0001-3765201920180441

BIEROZA MZ and HEATHWAITE AL (2015) Seasonal variation in phosphorus concentration-discharge hysteresis inferred from high-frequency in situ monitoring. *J. Hydrol.* **524** 333–347. https://doi.org/10.1016/j.jhydrol.2015.02.036

BOWES MJ, JARVIE HP, HALLIDAY SJ, SKEFFINGTON RA, WADE AJ, LOEWENTHAL M, GOZZARD E, NEWMAN JR and PALMER-FELGATE EJ (2015) Characterising phosphorus and nitrate inputs to a rural river using high-frequency concentration-flow relationships. *Sci. Total Environ.* **511** 608–620. https://doi.org/10.1016/j.scitotenv.2014.12.086

BOWES MJ, NEAL C, JARVIE HP, SMITH JT and DAVIES HN (2010) Predicting phosphorus concentrations in British rivers resulting from the introduction of improved phosphorus removal from sewage effluent. *Sci. Total Environ.* **408** (19) 4239–4250. https://doi.org/10.1016/j.scitotenv.2010.05.016

BOWES MJ, SMITH JT, JARVIE HP and NEAL C (2008) Modelling of phosphorus inputs to rivers from diffuse and point sources. *Sci. Total Environ.* **395** (2–3) 125–138. https://doi.org/10.1016/j.scitotenv.2008.01.054

BRAZILIAN NATIONAL ENVIRONMENT COUNCIL (2005) CONAMA 357/2005. Diário Oficial da República Federativa do Brasil, Brasília, Brasil (in Portuguese).

CASTELLANO L, AMBROSETTI W, BARBANTI L and ROLLA A (2010) The residence time of the water in Lago Maggiore (N. Italy): First results from an Eulerian-Lagrangian approach. *J. Limnol.* **69** (1) 15–28.

CHAPRA SC (2008) *Surface Water-Quality Modeling.* Waveland Press, Long Grove, IL. 844 pp.

CHAPRA SC and CANALE RP (1991) Long-term phenomenological model of phosphorus and oxygen for stratified lakes. *Water Res.* **26** (6) 707–715. https://doi.org/10.1016/0043-1354(91)90046-s

CHAPRA SC, DOLAN DM and DOVE A (2016) Mass-balance modeling framework for simulating and managing long-term water quality for the lower Great Lakes. *J. Great Lakes Res.* **42** (6) 1166–1173. https://doi.org/10.1016/j.jglr.2016.04.008

CHEN D, HU M, GUO Y and DAHLGREN RA (2015) Reconstructing historical changes in phosphorus inputs to rivers from point and nonpoint sources in a rapidly developing watershed in eastern China, 1980-2010. *Sci. Total Environ.* **533** 196–204. https://doi.org/10.1016/j.scitotenv.2015.06.079

COLE TM and WELLS SA (2018) CE-QUAL-W2: A two-dimensional, laterally averaged, hydrodynamic and water quality model, Version 4.1. Portland State University, Portland. 150 pp.

CULLIS JDS, ROSSOUW N, DU TOIT G, PETRIE D, WOLFAARDT G, DE CLERCQ W and HORN A (2018) Economic risks due to declining water quality in the Breede River Catchment. *Water SA.* **44** (3) 464–473. https://doi.org/10.4314/wsa.v44i3.14

DEUS R, BRITO D, MATEUS M, KENOV I, FORNARO A, NEVES R and ALVES CN (2013) Impact evaluation of a pisciculture in the Tucuruí reservoir (Pará, Brazil) using a two-dimensional water quality model. *J Hydrol.* **487** 1–12. https://doi.org/10.1016/j.jhydrol.2013.01.022

FISCHER HB, KOH EJLR, IMBERGER J and BROOKS NH (1979) *Mixing in Inland and Coastal Waters.* Academic Press, San Diego. 483 pp.

FRAGA RF, ROCHA SMG and LIMA NETO IE (2020) Impact of flow conditions on coliform dynamics in an urban lake in the Brazilian semiarid. *Urban Water J.* **17** (1) 43–53. https://doi.org/10.1080/1573062X.2020.1734948

JANSSEN ABG, VAN WIJK D, VAN GERVEN LPA, BAKKER ES, BREDERVELD RJ, DEANGELIS DL, JANSE JH and MOOIJ WM (2019) Success of lake restoration depends on spatial aspects of nutrient loading and hydrology. *Sci. Total Environ.* **679** 248–259. https://doi.org/10.1016/j.scitotenv.2019.04.443

JONES ID and ELLIOTT JA (2007) Modelling the effects of changing retention time on abundance and composition of phytoplankton species in a small lake. *Freshwater Biol.* **52** (6) 988–997. https://doi.org/10.1111/j.1365-2427.2007.01746.x

KIM D, KIM Y and KIM B (2019) Simulation of eutrophication in a reservoir by CE-QUAL-W2 for the evaluation of the importance of point sources and summer monsoon. *Lake Reserv. Manag.* **35** (1) 64–76. https://doi.org/10.1080/10402381.2018.1530318

LASPIDOU C, KOFINAS D, MELLIOS N, LATINOPOULOS D and PAPADIMITRIOU T (2017) Investigation of factors affecting the trophic state of a shallow Mediterranean reconstructed lake. *Ecol. Eng.* **103** 154–163. https://doi.org/10.1016/j.ecoleng.2017.03.019

LEWIS WM (2000) Basis for th.e protection and management of tropical lakes. *Lake Reserv. Res. Manage.* **5** 35–48. https://doi.org/10.1046/j.1440-1770.2000.00091.x

LIMA NETO IE (2019) Impact of artificial destratification on water availability of reservoirs in the Brazilian semiarid. *Ann. Braz. Acad. Sci.* **91** (3) 1–12. https://doi.org/10.1590/0001-3765201920171022

LIMA NETO IE, MEDEIROS PHA, COSTA AC, WIEGAND MC, BARROS ARM and BARROS MUG (2022) Assessment of phosphorus loading dynamics in a tropical reservoir with high seasonal water level changes. *Sci. Total Environ.* **815** 1–10. https://doi.org/10.1016/j.scitotenv.2021.152875

LIMA NETO IE, WIEGAND MC and DE ARAÚJO JC (2011) Sediment redistribution due to a dense reservoir network in a large semiarid Brazilian basin. *Hydrol. Sci. J.* **56** (2) 319–333. https://doi.org/10.1080/02626667.2011.553616

LIRA CCS, MEDEIROS PHA and LIMA NETO IE (2019) Modelling the impact of sediment management on the trophic state of a tropical reservoir with high water storage variations. *Ann. Braz. Acad. Sci.* **92** 1–18. https://doi.org/10.1590/0001-3765202020181169

MAHANTY MM, MOHANTY PK, PATTNAIK AK, PANDA US, PRADHAN S and SAMAL RN (2016) Hydrodynamics, temperature/salinity variability and residence time in the Chilika lagoon during dry and wet period: Measurement and modeling. *Cont. Shelf Res.* **125** 28–43. https://doi.org/10.1016/j.csr.2016.06.017

MEKONNEN MM and HOEKSTRA AY (2018) Global anthropogenic phosphorus loads to freshwater and associated grey water footprints and water pollution levels: a high-resolution global study. *Water Resour. Res.* **54** (1) 345–358. https://doi.org/10.1002/2017wr020448

MESSAGER ML, LEHNER B, GRILL G, NEDEVA I and SCHMITT O (2016) Estimating the volume and age of water stored in global lakes using a geo-statistical approach. *Nat. Commun.* **7** 1–11. https://doi.org/10.1038/ncomms13603

MESQUITA JFB, LIMA NETO IE, RAABE A and ARAÚJO JC (2020) The influence of hydroclimatic conditions and water quality on evaporation rates of a tropical lake. *J. Hydrol.* **590** 1–13. https://doi.org/10.1016/j.jhydrol.2020.125456

MOCKLER EM, DEAKIN J, ARCHBOLD M, GILL L, DALY D and BRUEN M (2017) Sources of nitrogen and phosphorus emissions to Irish rivers and coastal waters: Estimates from a nutrient load apportionment framework. *Sci. Total Environ.* **601–602** 326–339. https://doi.org/10.1016/j.scitotenv.2017.05.186

MOURA DS, LIMA NETO IE, CLEMENTE A, OLIVEIRA S, PESTANA CJ, APARECIDA DE MELO M and CAPELO-NETO J (2020) Modeling phosphorus exchange between bottom sediment and water in tropical semiarid reservoirs. *Chemosphere.* **246** 1–10. https://doi.org/10.1016/j.chemosphere.2019.125686

NAMUGIZE JN and JEWITT GPW (2018) Sensitivity analysis for water quality monitoring frequency in the application of a water quality index for the uMngeni River and its tributaries, KwaZulu-Natal, South Africa. *Water SA.* **44** (4) 516–527. https://doi.org/10.4314/wsa.v44i4.01

DE OLIVEIRA TF, DE SOUSA BRANDÃO IL, MANNAERTS CM, HAUSER-DAVIS RA, FERREIRA DE OLIVEIRA AA, FONSECA SARAIVA AC, DE OLIVEIRA MA and ISHIHARA JH (2020) Using hydrodynamic and water quality variables to assess eutrophication in a tropical hydroelectric reservoir. *J. Environ. Manage.* **256** 1–11. https://doi.org/10.1016/j.jenvman.2019.109932

PACHECO CHA and LIMA NETO IE (2017) Effect of artificial circulation on the removal kinetics of cyanobacteria in a hypereutrophic shallow lake. *J. Environ. Eng.* **143** (12) 1–8. https://doi.org/10.1061/(ASCE)EE.1943-7870.0001289

PILOTTI M, SIMONCELLI S and VALERIO G (2014) A simple approach to the evaluation of the actual water renewal time of natural stratified lakes. *Water Resour. Res.* **50** (4) 2830–2849.

RABELO UP, DIETRICH J, COSTA AC, SIMSHAUSER MN, SCHOLZ FE, NGUYEN VT and LIMA NETO IE (2021) Representing a dense network of pounds and reservoirs in a semi-distributed dryland catchment model. *J. Hydrol.* **603** 1–24. https://doi.org/10.1016/j.jhydrol.2021.127103

RATTAN KJ, CORRIVEAU JC, BRUA RB, CULP JM, YATES AG and CHAMBERS PA (2017) Quantifying seasonal variation in total phosphorus and nitrogen from prairie streams in the Red River Basin, Manitoba Canada. *Sci. Total Environ.* **575** 649–659. https://doi.org/10.1016/j.scitotenv.2016.09.073

RAULINO JB, SILVEIRA CS and LIMA NETO IE (2021) Trophic state changes of semi-arid reservoirs as a function of the hydro-climatic variability. *J. Arid Environ.* **185** 1321–1336. https://doi.org/10.1016/j.jaridenv.2020.104321

ROCHA MJD and LIMA NETO IE (2021) Modeling flow-related phosphorus inputs to tropical semiarid reservoirs. *J. Environ. Manage.* **295** 1–16. https://doi.org/10.1016/j.jenvman.2021.113123

ROCHA MJD and LIMA NETO IE (2022) Internal phosphorus loading and its driving factors in the dry period of Brazilian semiarid reservoirs. *J. Environ. Manage.* **312** 1–16. https://doi.org/10.1016/j.jenvman.2022.114983

RUEDA F, MORENO-OSTOS E and ARMENGOL J (2006) The residence time of river water in reservoirs. *Ecol. Modell.* **191** (2) 260–274. https://doi.org/10.1016/j.ecolmodel.2005.04.030

SADEGHIAN A, CHAPRA SC, HUDSON J, WHEATER H and LINDENSCHMIDT KE (2018) Improving in-lake water quality modeling using variable chlorophyll a/algal biomass ratios. *Environ. Model. Softw.* **101** 73–85. https://doi.org/10.1016/j.envsoft.2017.12.009

SALAS HJ and MARTINO P (1991) A simplified phosphorus trophic state model for warm-water tropical lakes. *Water Res.* **25** (3) 341–350. https://doi.org/10.1016/0043-1354(91)90015-i

SHEN HH, CHENG AHD, WANG KH, TENG MH and LIU CCK (2002) *Environmental Fluid Mechanics: Theories and Applications.* ASCE, Reston, VA. 480 pp.

SOARES LMV, SILVA TF DAS G, VINÇON-LEITE B, ELEUTÉRIO JC, DE LIMA LC and NASCIMENTO N DE O (2019) Modelling drought impacts on the hydrodynamics of a tropical water supply reservoir. *Inland Waters.* **9** (4) 422–437. https://doi.org/10.1080/20442041.2019.1596015

TERRY JA, SADEGHIAN A, BAULCH HM, CHAPRA SC and LINDENSCHMIDT KE (2018) Challenges of modelling water quality in a shallow prairie lake with seasonal ice cover. *Ecol Modell.* **384** 43–52. https://doi.org/10.1016/j.ecolmodel.2018.06.002

TONÉ AJA, PACHECO CHA and LIMA NETO IE (2017) Circulation induced by diffused aeration in a shallow lake. *Water SA.* **43** (1) 36–41. https://doi.org/10.4314/wsa.v43i1.06

TONG Y, LI J, QI M, ZHANG X, WANG M, LIU X, ZHANG W, WANG X, LU Y and LIN Y (2019) Impacts of water residence time on nitrogen budget of lakes and reservoirs. *Sci Total Environ.* **646** 75–83. https://doi.org/10.1016/j.scitotenv.2018.07.255

VOLLENWEIDER RA (1968) Scientific fundamentals of the eutrophication of lakes and flowing waters with particular reference to phosphorus as factors in eutrophication. Tech. Rept. DAS/C81/68. Organisation for Economic Co-operation and Development, Paris. 169–170. https://doi.org/10.4319/lo.1970.15.1.0169

WAN Y, QIU C, DOERING P, ASHTON M, SUN D and COLEY T (2013) Modeling residence time with a three-dimensional hydrodynamic model: Linkage with chlorophyll a in a subtropical estuary. *Ecol. Modell.* **268** 93–102. https://doi.org/10.1016/j.ecolmodel.2013.08.008

WIEGAND MC, DO NASCIMENTO ATP, COSTA AC and LIMA NETO IE (2021) Trophic state changes of semi-arid reservoirs as a function of the hydro-climatic variability. *J. Arid Environ.* **184** 1–9. https://doi.org/10.1016/j.jaridenv.2020.104321

XU C, ZHANG J, BI X, XU Z, HE Y and GIN KYH (2017) Developing an integrated 3D-hydrodynamic and emerging contaminant model for assessing water quality in a Yangtze Estuary Reservoir. *Chemosphere.* **188** 218–230. https://doi.org/10.1016/j.chemosphere.2017.08.121

ZHANG B, DING W, XU B, WANG L, LI Y and ZHANG C (2020) Spatial characteristics of total phosphorus loads from different sources in the Lancang River Basin. *Sci. Total Environ.* **722** 1–14. https://doi.org/10.1016/j.scitotenv.2020.137863

ZHANG C, BRETT MT, BRATTEBO SK and WELCH EB (2018) How well does the mechanistic water quality model CE-QUAL-W2 represent biogeochemical responses to climatic and hydrologic forcing? *Water Resour Res.* **54** (9) 6609–6624. https://doi.org/10.1029/2018wr022580