Phosphorus dynamics in a highly polluted urban drainage channel-shallow reservoir system in the Brazilian semiarid

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Abstract: This paper investigates phosphorus dynamics in a highly polluted system composed of a drainage channel followed by a shallow reservoir in the city of Fortaleza, Brazilian semiarid. During the dry season, significant non-point source loads of total phosphorus originated from residences unconnected to sewers were identified along the channel, resulting in an increasing flow rate of untreated sewage towards the reservoir. During the rainy season, as a consequence of dilution, phosphorus concentrations decreased by about 5-fold. The results also revealed that the reservoir was acting similarly to a waste stabilization pond, with phosphorus removal efficiency of about 33%. Assuming one-dimensional flow for the channel and complete mixing for the reservoir, it was possible to adjust phosphorus decay coefficients of $k_c = 2.2$ day^{-1} and $k_r = 22.8$ year^{-1}, respectively, which were higher than their corresponding values available in the literature. This was attributed mainly to the relatively high temperatures and shallow water depths. The results also revealed an inverse dependence of k_c and k_r on water and wind velocity, with potential thresholds of respectively 0.3 and 5.0 m/s for resuspension of bed sediments and internal phosphorus loading.

Key words: diffuse pollution, eutrophication, nutrients, semiarid, urbanization, water quality modeling.

INTRODUCTION

Eutrophication of urban waters is a worldwide problem which is associated with high phosphorus (P) loadings (Ruley and Rusch 2004, Bedore et al. 2008, Nyenje et al. 2014, Hobbie et al. 2017). In Brazil, despite the use of separate systems for sanitary sewer and stormwater runoff, only 50% of residences are connected to a sanitary sewer system and only 43% of the sewage is treated (SNIS – National Information System on Sanitation 2015). As a consequence, several urban water bodies are already hypereutrophic and need urgent restoration (Pacheco and Lima Neto 2017).

Previous studies on P modeling in water bodies have been reported by many authors (Vollenweider 1968, Castagnino 1982, Brown and Barnwell 1987, Havis and Ostendorf 1989, Salas and Martino 1991, Ruley and Rusch 2004, Pelletier and Chapra 2005, Chao et al. 2006, Lewis et al. 2007, Bowes et al. 2008, Chapra et al. 2016). The one-dimensional

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P transport equation is normally used for rivers and streams (Brown and Barnwell 1987). On the other hand, most studies related to lakes applied or modified the classical zero-dimensional P balance model of Vollenweider (1968) for temperate regions, which has been adapted by Salas and Martino (1991) for tropical lakes. Comprehensive reviews of P models and more sophisticated water quality models including nutrient dynamics for both rivers and lakes can be found in Shen et al. (2002) and Chapra (2008). Nevertheless, understanding P dynamics in hot arid/semiarid regions is still a problem that needs to be tackled. Moreover, the literature is also scarce with respect to P modeling in urban catchments, especially when a few residences are connected to sewers.

The main objective of this paper was to contribute to the understanding of P dynamics in a highly polluted urban drainage channel-shallow reservoir system located in the city of Fortaleza, in the Brazilian semiarid. More specifically, the objectives were: (1) to quantify non-point source loads of P along the channel from residences unconnected to sewers, (2) to investigate the flow conditions and their impacts on P dynamics, and (3) to adjust P decay coefficients for both the channel and the reservoir, and compare the results with those available in the literature for non-semiarid regions.

**MATERIALS AND METHODS**

STUDY AREA

The study was performed in an urban drainage channel-shallow reservoir system in Fortaleza, Ceará, Brazil, as shown schematically in Figure 1. Ceará is one of the eight Brazilian States located within the drought polygon, a highly populated Brazilian semiarid region, where thousands of surface reservoirs have been constructed to store water in the rainy periods and compensate the deficits in the dry periods (see Lima Neto et al.

2011). Fortaleza is the capital city of Ceará. This touristic city has more than 2.6 million inhabitants and the highest population density among Brazilian capitals ($> 8,400$ people/km^2). While some parts of the city present a Human Development Index (HDI) very high (> 0.9), other suburban areas have a very low index (< 0.2), which are characterized by the predominance of residences unconnected to the sanitary sewer system. The channel-lake system studied in this paper is located within one of these city areas with very low HDI.
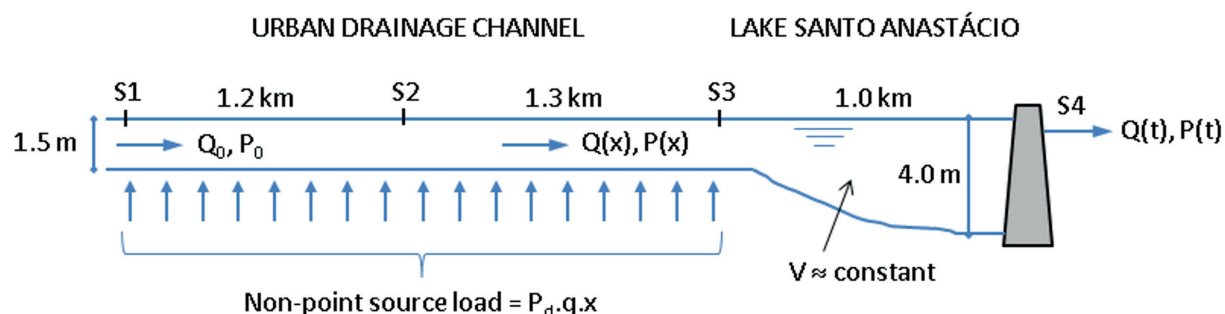
Figure 2 sketches the urban drainage channel-shallow reservoir system. The channel is 2.5 km long and presents a rectangular cross section in concrete with height of 1.5 m and width of 5 m. Upstream the channel, there is a lake called Parangaba with maximum depth of about 5 m and capacity of about 1.0 hm^3. Both this lake and the channel are surrounded by residences unconnected to the sewer system, which contribute with non-point source loads from untreated sewage along the perimeter of these water bodies. The reservoir (Lake Santo Anastácio) is located downstream the channel. It has a maximum depth of about 4 m and capacity of approximately 0.3 hm^3 (Araújo and Lima Neto 2018). Even in the dry season, the reservoir is constantly full, as it receives continuously untreated sewage from the channel. The reservoir discharges the outflows through a rectangular weir 2 m wide to the Maranguapinho river, one of the two main natural drainage systems of the city of Fortaleza (see Fig. 1).

FIELD STUDY AND DATA ANALYSIS

The field surveys were conducted during the rainy and dry seasons of May 2013 – February 2014 to assess the variability of flow rates and water quality in the channel-reservoir system. A propeller anemometer (Omni Instruments) was used to measure water velocities at sections S1, S2, S3 and S4 (see Figs. 1 and 2). Hence, with the aim of a ruler, it was possible to obtain the water depth
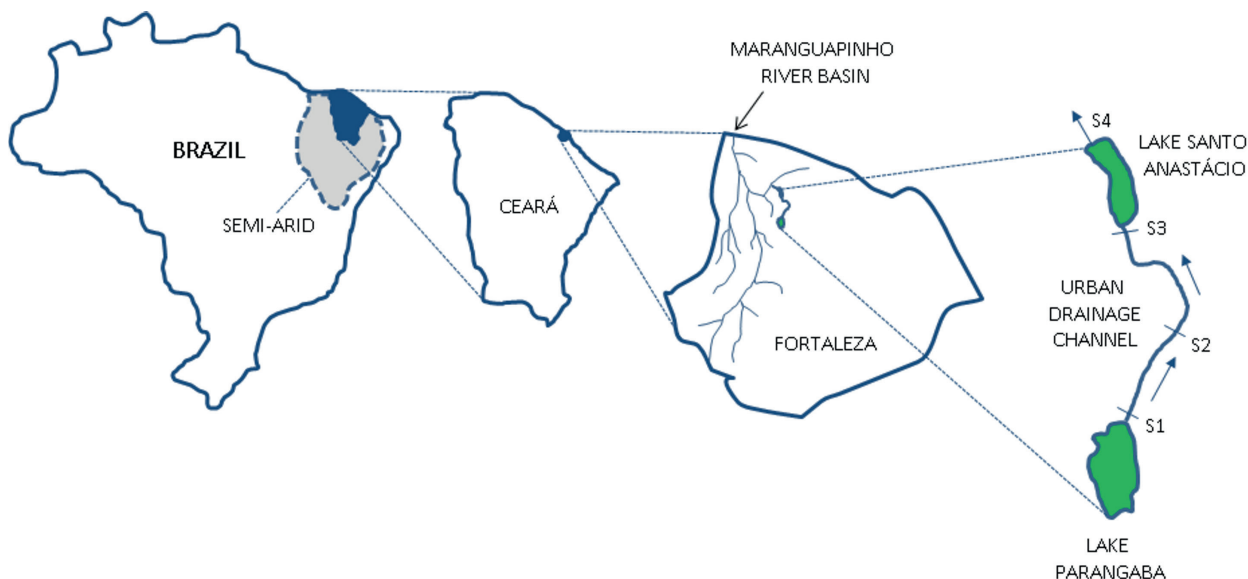
Figure 1 - Schematic of the urban drainage channel-shallow reservoir system located within the Maranguapinho River Basin, in the city of Fortaleza, Ceará State (Brazilian semiarid). Measurement sections S1 – S4 are also indicated.

Figure 2 - Details of the urban drainage channel-shallow reservoir system. A distributed load of P from residences unconnected to the sewer system is also indicated.

and estimate the flow rate at each cross-section of the channel/reservoir for different flow conditions. Several culverts and illegal PVC pipes were also identified along the channel. The flow rates at some of these culverts/pipes were also measured with the aim of a bucket. Water samples were collected at each cross-section of the channel/reservoir and at some culverts/pipes using Van Dorn bottles in order to investigate the impact of non-point source loads from informal residences on P concentration along the channel/reservoir. The samples were analyzed for total phosphorus (P) in the Laboratório de Química Ambiental (LAQA) at the Universidade Federal do Ceará/ UFC, following the Standard Methods (APHA 2005). Hydrological parameters including precipitation and wind velocity (at 10 m above ground) were also measured in a meteorological station located near the reservoir.

MATHEMATICAL MODELING

A general P balance equation can be written as following:

$$\frac{\partial P}{\partial t} + \frac{\partial uP}{\partial x} + \frac{\partial vP}{\partial y} + \frac{\partial wP}{\partial z} = \frac{\partial}{\partial x}\left(\varepsilon_x \frac{\partial P}{\partial x}\right) + \frac{\partial}{\partial y}\left(\varepsilon_y \frac{\partial P}{\partial y}\right) + \frac{\partial}{\partial z}\left(\varepsilon_z \frac{\partial P}{\partial z}\right) \pm S \pm R \quad (1)$$

in which P is total phosphorus concentration, t is time, and x, y and z are the longitudinal, transversal and vertical coordinates, respectively. In the LHS of

Eq. (1), the first term refers to accumulation and the second-fourth terms refer to advection. In the RHS of Eq. (1), the first-third terms refer to dispersion, where ε_x, ε_y, and ε_z are the turbulent dispersion coefficients, while S and R are the external and internal sources (+) or sinks (-) of P, respectively.

In the channel, assuming one-dimensional, steady-state and uniform flow in the x direction (see Fig. 2); neglecting the dispersion terms; and considering a linear increase in the flow rate given by $Q = Q_0 + qx$, where q is a constant rate of flow increase, Eq. (1) can be reduced to:

$$(Q_0 + qx)\frac{dP}{dx} = P_d q - Pq - k_c A_0 P \qquad (2)$$

in which P_d is the total phosphorus concentration in the lateral flow (untreated sewage), k_c is a coefficient of P decay in the channel due to algal uptake and settling, and A_0 is the area of the flow at the inlet. Thus, considering a constant velocity (U_0) along the channel, Chapra (2008) gave the following analytical solution to Eq. (2):

$$P = \left[P_0 e^{-k_c \frac{x}{U_0}} + \frac{P_d q \left(1 - e^{-k_c \frac{x}{U_0}}\right)}{k_c A_0} \right] \left(\frac{U_0}{U_0 + qx/A_0}\right) \qquad (3)$$

In the reservoir, assuming complete mixing of the flow and a constant lake volume V (see Fig. 2), Eq. (1) can be reduced to:

$$V\frac{dP}{dt} = W - QP - k_r VP \qquad (4)$$

in which W and Q are the average phosphorus load and water inflow to the reservoir, respectively, and k_r is a coefficient of P decay in the reservoir due to algal uptake and settling. Chapra (2008) provided the following analytical solution to Eq. (4):

$$P = P_0 e^{-\left(\frac{Q}{V} + k_r\right)t} + \frac{W}{(Q + k_r V)} \left[1 - e^{-\left(\frac{Q}{V} + k_r\right)t}\right] \qquad (5)$$

Finally, Eqs. (3) and (5) were adjusted to field data in order to fit the P decay coefficients k_c and k_r for different flow conditions. The fitted values were analyzed as a function of water and wind velocities and contrasted to the values reported in the literature for non-semiarid regions.

RESULTS AND DISCUSSION

Figure 3 shows the seasonal variation of monthly averaged flow rates and phosphorus concentrations measured at different cross-sections (S1 – S4) in the channel-reservoir system. Observe that the flow rates were calculated from measurements of water depth (~ 0.1 – 0.4 m) and velocity (~ 0.1 – 0.4 m/s), and that a sediment layer with thickness of approximately 0.3 m was also identified at the bottom of the channel. The results shown in Fig. 3a indicate much larger flow rates during rainy events, with maximum values of about 600 – 1,000 L.s^{-1} occurring in June 2013. As a consequence of urban runoff in the catchment, there was a significant increase in the flow rate along the channel (S1 – S3), while evaporation losses across the lake surface area slightly reduced the flow rate at the reservoir outlet (S4). On the other hand, minimum flow rates of about 20 – 80 L.s^{-1} occurred in November 2013. Note that a massive increase in the flow rate along the channel (~ 4-fold) was also observed during the dry period, which is attributed to the untreated sewage flow contributions from residences unconnected to the sewers. On the other hand, P values shown in Fig. 3b ranged from about 0.5 to 7.0 mg.L^{-1}, which were much higher than the limits allowed for natural rivers and streams (0.1 mg.L^{-1}) and lakes (0.03 mg.L^{-1}), according to the Resolução 357/05 (Ministério do Meio Ambiente and CONAMA 2005). As a result of dilution, P concentrations in the rainy season (high flows) were roughly 5-fold lower than those in the dry season (low flows). The same trend has been reported by Bowes et al. (2008) for similar ranges of flow rates and phosphorus concentrations in rivers. This
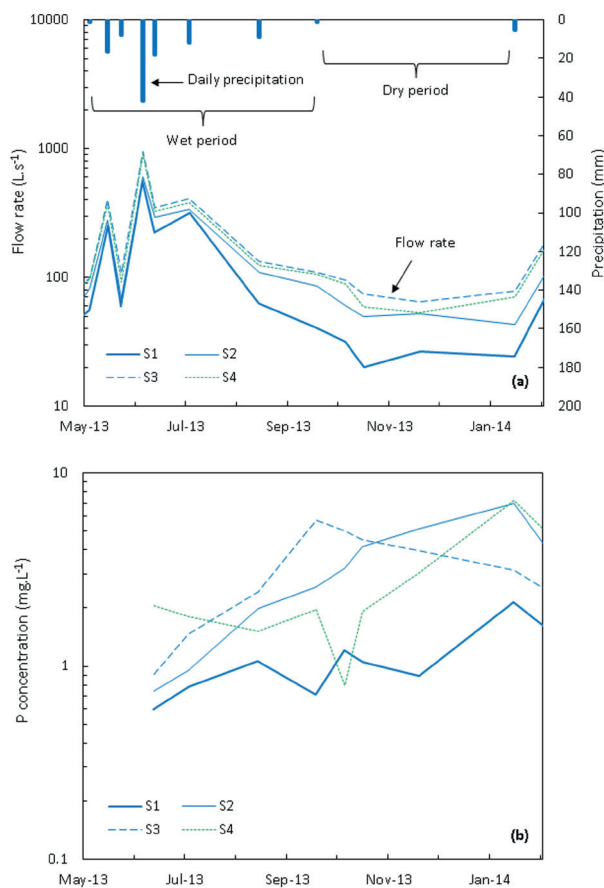
Figure 3 - Seasonal variation of **(a)** flow rate and **(b)** total phosphorus concentration measured at different cross-sections S1 – S4 along the channel-reservoir system.

implies that non-sewage diffused loads of P from the studied catchment were not relevant.

Figure 4 depicts box-plots of P concentrations measured at different locations, including the four cross-sections S1 – S4 and a culvert located between S1 and S2. The mean P concentration increased along the channel from about 1 to 3 mg.L^{-1}, which is attributed to the dominant effect of lateral sewage inputs over the effects of uptake/settling. Note that typical P concentrations at the culverts were about 6 mg.L^{-1}, which are within the ranges reported by Chapra (2008) for untreated domestic sewage. On the other hand, mean P concentration decreased through the reservoir from about 3 to 2 mg.L^{-1}, resulting in a removal efficiency of about 33%, similarly to waste stabilization ponds (see Von

Sperling 2007). However, it is interesting to stress that mean P concentration presented a progressive increase when comparing S1 to S4, which might result in serious water quality impacts downstream in the Maranguapinho River Basin (see Fig. 1).

Typical hourly variations of flow rates measured during the dry period at different cross-sections and culverts are shown in Fig. 5. The data confirms that in the absence of precipitation, the increase in the flow rate along the channel was indeed because of the lateral sewage flow from informal residences. Note that about 20 culverts of 30-50 cm in diameter and more than 200 small pipes of 5-10 cm were identified over the 2.5 km reach of the channel. Figure 5 also suggests that during the dry season the flow rates were approximately constant, consistently with the results presented in Fig. 3a.
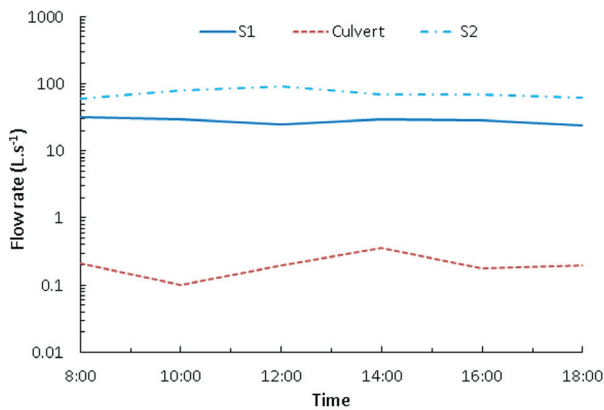
Figure 6 shows the rates of flow increase along the urban drainage channel as a function of daily precipitation. The results indicate a direct relationship between these two variables and the following correlation was adjusted with coefficient of determination $R^2 = 0.5169$:

$$q = 20.366e^{0.0599.Precipitation} \qquad (6)$$

Thus, when the daily precipitation is nil, Eq. (6) yields a value of q = 20 L.s^{-1}.km^{-1}. It is interesting to point out that this value is about 20 times larger than the maximum storm water infiltration rate of 1.0 L.s^{-1}.km^{-1} recommended by the Norma Técnica – NBR 9649 (ABNT 1986). On the other hand, when the daily precipitation is of the order of 40 mm, Eq. (6) gives a much larger value of q = 200 l.s^{-1}.km^{-1}). Data available in Araújo (2016) provides a number of 42,036 inhabitants in the drainage area of the studied channel as well as a sewage contribution per capita of about 136 L/day. Thus, neglecting the small coverage of sewer systems in this area, we obtain q = 26 L.s^{-1}.km^{-1}, which is close to the above-mentioned value of
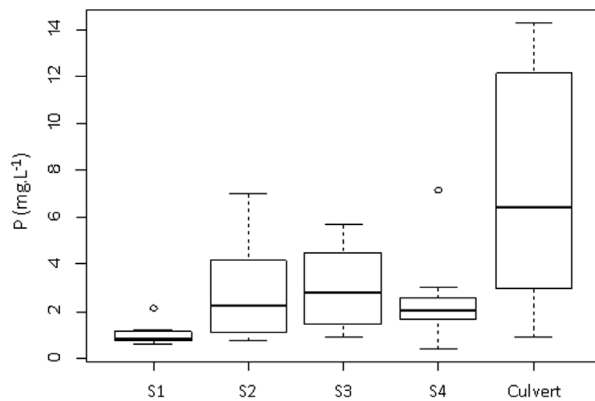
Figure 4 - P concentrations obtained at different locations, including the four cross-sections S1 – S4 and a culvert located between S1 and S2.


Figure 5 - Hourly variation of flow rates measured in November 14, 2013 (dry season) at S1 and S2, and at a culvert between these two cross-sections.
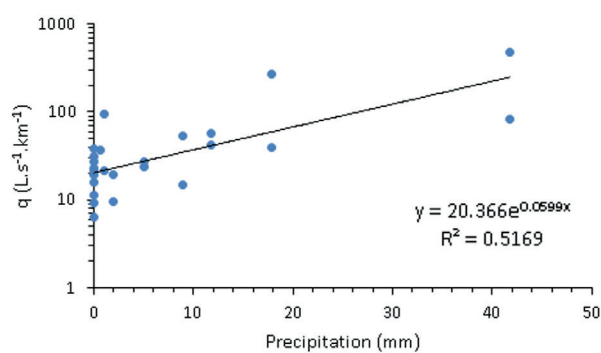
Figure 6 - Rates of flow increase obtained along the channel as a function of daily precipitation.

about 20 L.s^{-1}.km^{-1} observed along the channel during the dry period. This corroborates the idea that most of the lateral inflow to the channel comes from untreated domestic sewage discharges from residences unconnected to the sewers.

Figure 7 shows the total phosphorus decay coefficients fitted for the channel (k_c) and reservoir (k_r), which were obtained respectively by adjusting Eqs. (3) and (5) to field data for different flow conditions. Error bars represent standard deviations obtained when more than two data points were available. The results show an inverse dependence of these coefficients on water and wind velocity, indicating clear thresholds of about 0.3 and 5.0 m/s, respectively, after which these coefficients became negative, suggesting the possible domination of resuspension of bed sediments and internal P loading over degradation of P due to uptake/settling, as pointed out by Søndergaard et al. (2003) and Welch and Cooke (2005) for shallow lakes. Note that the above-mentioned values are close to the limits of 0.2 m/s (water velocity) and 6.0 m/s (wind velocity) reported by Bengtsson and Hellstrom (1992) and Madsen et al. (2001) for resuspension of bed sediments in streams and shallow lakes, respectively. Nevertheless, the average values of k_c (= 2.2 day^{-1}) and k_r (= 22.8 year^{-1}) were positive. For rivers and streams, Chapra (2008) reported a maximum value of k_c = 0.8 day^{-1}. Correcting this value to the present water temperature (~28°C), k_c becomes about 1.8 day^{-1}, which is close to the value obtained here (k_c = 2.2 day^{-1}). Two possible reasons for the high value of k_c adjusted in this study are the relatively low water depths and the high concentrations of organic matter, which may increase the settling rates, as k_c is a function of v/H, where H is the water depth and v is the apparent settling velocity which is expected to increase with particle size (see García 2008). On the other hand, the value of k_r adjusted here is about 4.1 and 2.0 times higher than those obtained by using the correlations of Vollenweider (1968) and Salas and Martino (1991) for temperate and tropical lakes,
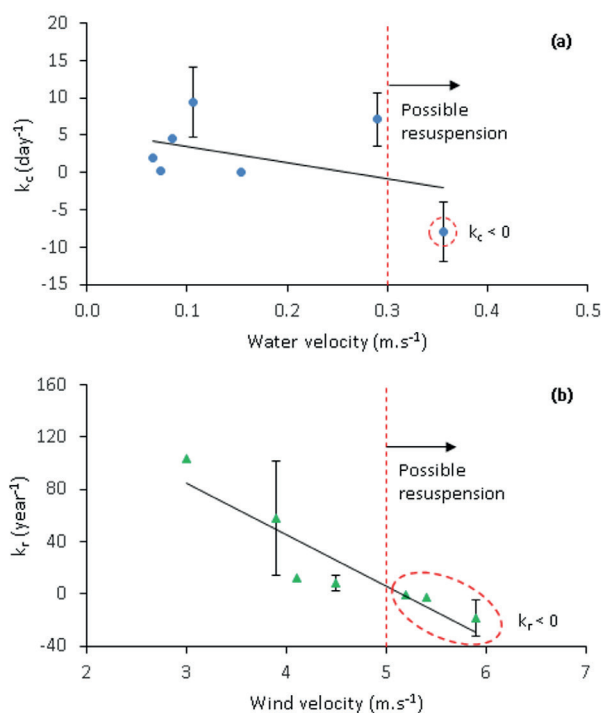
Figure 7 - Inverse dependence of P decay coefficient on water and wind velocities obtained for **(a)** the channel and **(b)** the reservoir, respectively, indicating potential thresholds (dashed lines) for resuspension of bed sediments/internal P loading. Solid lines are curves fitted to the data and error bars represent standard deviations.

respectively. Note that the temperature correction procedure of Castagnino (1982) yields a value of k_r of about 28 year^{-1}, which is close to the adjusted value ($k_r = 22.8$ year^{-1}) for the present hot semiarid reservoir.

CONCLUSIONS

Field studies performed in a highly polluted urban drainage channel-shallow reservoir system in the Brazilian semiarid revealed significant non-point source loads of total phosphorus from residences unconnected to the sewer system. As a consequence of dilution, phosphorus concentrations decreased by about 5-fold during the rainy season but were still much larger than the limits allowed by the CONAMA 357/05. Average phosphorus removal efficiency in the reservoir was 33%, which suggests that it was functioning similarly to a waste

stabilization pond. Adjusting a one-dimensional model for the channel and a complete mixing model for the reservoir to the field data, it was possible to fit phosphorus decay coefficients of $k_c = 2.2$ day^{-1} and $k_r = 22.8$ year^{-1}, respectively, which were higher than the values in the literature, possibly because of the relatively high temperatures and shallow water depths in the present study. The results also indicated that k_c and k_r are inversely dependent on water and wind velocities, with potential thresholds of 0.3 and 5.0 m/s for resuspension of bed sediments and internal phosphorus loading, respectively.

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AUTHOR CONTRIBUTIONS

Germário M. Araújo conducted the field and laboratory studies, analyzed the data, and drafted the manuscript. Iran E. Lima Neto helped to draft the field and laboratory planning, analyzed the data, performed the mathematical modeling, and contributed to the manuscript. Helena Becker helped to conduct laboratory studies, processed the experimental data, and gave critical feedback to the manuscript. All authors have approved the final article.

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