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Alana Jade de Lima Bezerra

PHOSPHORUS RELEASE FROM SEDIMENTS AND THE ROLE OF OXYGEN AND TROPHIC STATE

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Dissertação apresentada ao Programa de Pós-graduação *stricto sensu*, em Engenharia Sanitária, da Universidade Federal do Rio Grande do Norte, como requisito parcial à obtenção do título de Mestre em Engenharia Sanitária.

Orientador: Dr.ª Fabiana Araújo
Coorientadora: Prof.ª Drª Vanessa Becker

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Apresentação

Esse trabalho refere-se a um experimento realizado com sedimento de um reservatório localizado na região semiárida brasileira que apresenta problemas de eutrofização. Uma das principais consequências da eutrofização é o aumento da biomassa algal, que causa depleção do oxigênio na água, afetando os ecossistemas aquáticos de modo a diminuir a biodiversidade e degradando ainda mais a qualidade da água nesses sistemas.

A eutrofização é um processo natural que pode ser atenuado através da diminuição do aporte de nutrientes, principalmente o fósforo, já que este é limitante da proliferação do fitoplâncton. Muito embora os aportes externos, como lançamento de efluentes, atividades pecuárias e agricultura às margens dos reservatórios, possam ser minimizados ou até mesmo cessados, essas ações podem não ser suficientes no controle da eutrofização. Isso deve-se ao fato de que o sedimento pode agir como fertilizador interno de fósforo no reservatório durante longos períodos de tempo, principalmente em eventos de seca onde não há contribuição de nutrientes provenientes da bacia. As condições as quais mantém esse fósforo armazenado são muito diversas, podendo ser, por exemplo, a própria composição do sedimento, o pH do meio, a temperatura, as condições redox, a concentração de oxigênio. Qualquer mudança em algum desses parâmetros pode favorecer a liberação de fósforo de volta para a coluna d’água, fertilizando o sistema e perpetuando as condições eutróficas do corpo hídrico.

Por muito tempo se pensou, porém, que garantir a presença de oxigênio na interface sedimento-água fosse suficiente para o controle desse fenômeno. Porém, há muitos estudos que relatam a liberação de fósforo na presença de oxigênio. Além disso, há indícios que o grau de trofia da água também interfira nas taxas de liberação de fósforo do sedimento para a coluna d’água.

Portanto, o objetivo desse trabalho foi avaliar as características das taxas de liberação de fósforo em águas que apresentam diferentes gradientes de concentração de fósforo (água natural e deionizada), sob condições de hipoxia e presença de oxigênio.

ABSTRACT

Phosphorous (P) is a limiting nutrient of algal growth. Reducing input of point P sources of surface waters, although essential, is not enough towards mitigating eutrophication due to the P internal loading. There are numerous factors that can interfere on P release, including oxygen presence and trophic state of overlying water. Hence, our study aimed to analyze P fluxes concerning the oxygen presence (low and high oxygen) and the phosphorus concentrations of overlying water (natural and deionized water) utilizing several microcosms in order to simulate the proposed conditions. Overall, P fluxes were higher when a low P concentration overlying water situation was simulated under hypoxic conditions for both soluble reactive phosphorus (SRP) and dissolved organic phosphorus (DOP) fluxes. With natural overlying water, P release was greater also under hypoxic conditions, which is an indicative of higher inorganic P bonded to Al and FeOOH. When the P fluxes are analyzed temporally, we could notice that P fluxes were positive at the first seven days, then, mostly negative for the rest of the experiment. This indicates that, although P release is significant throughout the experiment, phosphorus behavior is dynamic in time. SRP fluxes for the 0-7 day interval showed interaction only with variation of P concentration in overlying water, while DOP fluxes exhibit only interaction with both O_2 and P concentrations. The 7-14 day interval indicates higher phosphorus retention in oxic conditions for both SRP and DOP fluxes. SRP fluxes were significantly changed with oxygen conditions, while DOP fluxes, with P concentration. Both SRP and DOP fluxes showed significant interaction between categorical factors. Thus, in semiarid regions such as Gargalheiras', P release might continue being a serious problem due to its high temperature and pH, low depth and elevated evaporation rates, which contributes to concentrate P in overlying water and induce anoxic conditions in sediment. Also, even if the rainy season come to dilute P in water, P release may be favored due to P gradient concentration due to the large P pool in sediments.

Keywords: Sediment-water interface; Phosphorus release; Eutrophication; Internal loading.

Resumo

O fósforo é um nutriente que limita o crescimento algal. A redução da entrada desses nutrientes nos corpos d'água através de fontes pontuais é essencial, porém não é suficiente para mitigar a eutrofização, devido à fertilização interna. Diversos fatores podem interferir na liberação de fósforo, incluindo a presença de oxigênio e o estado trófico da água. Desta forma, este trabalho visou analisar fluxos de fósforo quanto à presença de oxigênio (alta e baixa concentrações) e às concentrações de fósforo (água natural e deionizada) na água sobrejacente ao sedimento. No geral, os fluxos de P foram maiores quando uma situação de sobreposição de água na baixa concentração de fósforo foi simulada sob condições hipóxicas para os fluxos de fósforo reativo solúvel (SRP) e fósforo orgânico dissolvido (DOP). Com a água natural sobrejacente, a liberação de P também foi maior sob condições hipóxicas, o que é um indicativo de maior liberação de fósforo inorgânico ligado a Al e FeOOH. Quando os fluxos de P são analisados temporalmente, podemos notar que os fluxos de fósforo foram positivos nos primeiros sete dias e, em sua maioria, negativos para o restante do experimento. Isso indica que, embora a liberação de fósforo seja significativa durante todo o experimento, o comportamento do fósforo é dinâmico ao longo do tempo. Os fluxos de SRP para o intervalo de 0 a 7 dias mostraram interação apenas com a variação da concentração de P na água sobrejacente, enquanto os fluxos de DOP exibem apenas interação com as concentrações de O_2 e P. O intervalo de 7-14 dias indica maior retenção de fósforo em condições óxicas para os fluxos SRP e DOP. Para todo o intervalo estudado, os fluxos de SRP foram significativamente alterados com as condições de oxigênio, enquanto os fluxos de DOP, com concentração de P. Ambos os fluxos SRP e DOP mostraram interação entre fatores categóricos. Assim, em regiões semiáridas como a de Gargalheiras, a liberação de fósforo deve continuar sendo um problema devido às altas temperaturas e pH, baixas profundidades dos reservatórios e elevadas taxas de evaporação, que contribuem para concentrar o fósforo na água e induzir condições anóxicas no sedimento. Ainda, mesmo com a chegada das chuvas para haver diluição do fósforo, a liberação deste pode ser favorecida devido ao gradiente de concentração formado devido à alta concentração de fósforo no sedimento.

Palavras-chave: Interface água-sedimento; Liberação de fósforo; Eutrofização; Fertilização interna.

Introduction

Phosphorus (P) is considered a primary nutrient that limits phytoplankton growth. Excessive P is known as the main reason of eutrophication (Smith and Schindler, 2009), which affects water quality and may cause drastic modifications to the ecosystems consequently increasing the phytoplankton biomass (Schindler et al., 2008; Smith and Schindler, 2009; Søndergaard et al., 2003). Although major external P sources, such as rainfall, runoff, soil leaching, and industrial and municipal effluents had been somewhat controlled over the past years, overlying water may not improve considerably due to P release from sediments, well-known as internal loading (Marsden, 1989; Schindler, 2012). Even though sediments often act as adsorbent material, its uptake capacity is limited and might vary with diverse parameters, such as the dissolved oxygen concentration (Chen et al., 2015). One of the most acknowledged mechanisms of internal loading is the releasing of P under oxygen absence (Mortimer, 1941).

The oxygen control of P release from sediments is an enduring paradigm of limnology. Although many studies have been pointing out a strong correlation between oxygen depletion and P release, there is no experimental evidence that supports the reduction of a FeOOH-P complex as cause of P release in anoxic conditions, but this mechanism is still broadly accepted (Golterman, 2001; Marsden, 1989). Also, P release has been observed to occur under aerobic conditions (Boström et al., 1988; Jensen and Andersen, 1992). Hence, sedimentary P exchange must be considered as a complex process and the classical mechanism is may be effective only in special cases (Hupfer and Lewandowski, 2008; Olszewska et al., 2017).

Besides oxygen concentration in overlying water, sediment composition, temperature, pH, redox potential, salinity, mixing and microbial processes, and water column depth are considered key parameters for P release (Holdren and Armstrong, 1980; Wu et al., 2014; Yi et al., 2015). Moreover, when the P concentration in the overlying water is higher than that in the pore-water, the P in the overlying water diffuses into the pore-water, and then enters the sediments. When the P concentration in the overlying water is lower than that in the pore-water, P is released from the pore-water to the overlying water (Golterman, 2004). Therefore, the release rate may be affected by the concentration of mobile P in the surface of the sediments and by the trophic state of overlying water.

When P enters the sediment, it takes a role in the several chemical and biological processes and finally can be stored in the sediment permanently or released to the water column by various mechanisms (e.g. temperature elevation, microbial metabolism, different redox conditions, Fe reduction) (Søndergaard et al., 2003). However, chemical composition of sediments can be very different, this can sure influence the interactions between water and sediment, and that is why the different forms of P must be evaluated (Søndergaard et al., 2003). Most of the studies about P release usually focus on the soluble reactive phosphorus (SRP), frequently ignoring the dissolved organic phosphorus (DOP), which was earlier considered part of the refractory P pool. However, some papers have emphasised organic P compounds as an important portion of the released P pool, thus, being able to contribute to eutrophication of water bodies (Ahlgren et al., 2011; Wang et al., 2009). Due to the scarce investigations concerning their potential mobility and release parameters from sediments, it is of great importance to investigate what factors influence organic sediment on P turnover.

Due to the natural conditions of the Brazilian semiarid region and their human activities, its reservoirs often suffer with water shortage of quality (Barbosa et al., 2012). Rural activities such as agriculture and livestock are the main external source of nutrients that enter the reservoirs through leaching of the soil during the rainy seasons (Oliveira et al., 2014). Although these external loadings are less during the drought periods, phosphorus concentrations remain high because of the increase of water retention time and elevated evaporation rates that concentrates the phosphorus into the reservoirs (Braga et al., 2015). Drought events cause lowering of reservoir depths and the high temperatures, anoxic sediment, elevated pH and mixing conditions can also contribute to internal loading, which poses more risks to shallow lakes than deep lakes (Søndergaard et al., 2003). Moreover, some reservoirs located at semiarid regions are known to have large pools of P in its sediments, which can play an important role in internal loading (Cavalcante et al., 2018a, 2018b).

Therefore, the objective of this study was to understand the phosphorus release characteristics of different P concentration in overlying water under simulative low and high oxygen concentrations.

Material and Methods

Study area

The Gargalheiras Reservoir (Fig. 1) is situated on Piranhas-Açu drainage basin at Rio Grande do Norte state of northeastern Brazil. Köppen's classification shows the region's climate as tropical semiarid BS′h′ (Alvares et al., 2013). The rainy season usually goes from February to June; the region receives 550 mm year^{-1} of rain, on average, although suffered extreme droughts from 2012 to 2016, leading to a severe decrease of the volumes and surface areas of its reservoirs.

Gargalheiras has multiple uses, such as water supply (its priority use), irrigation, fishing, recreation and animal watering. The reservoir has a maximum capacity of 44.4 million m^3 and a maximum 26.5 m depth. In September 2016, the moment of sampling, its volume was 516,251 m^3 (1.1% of capacity) and the depth was 6 m (SEMARH, 2017)

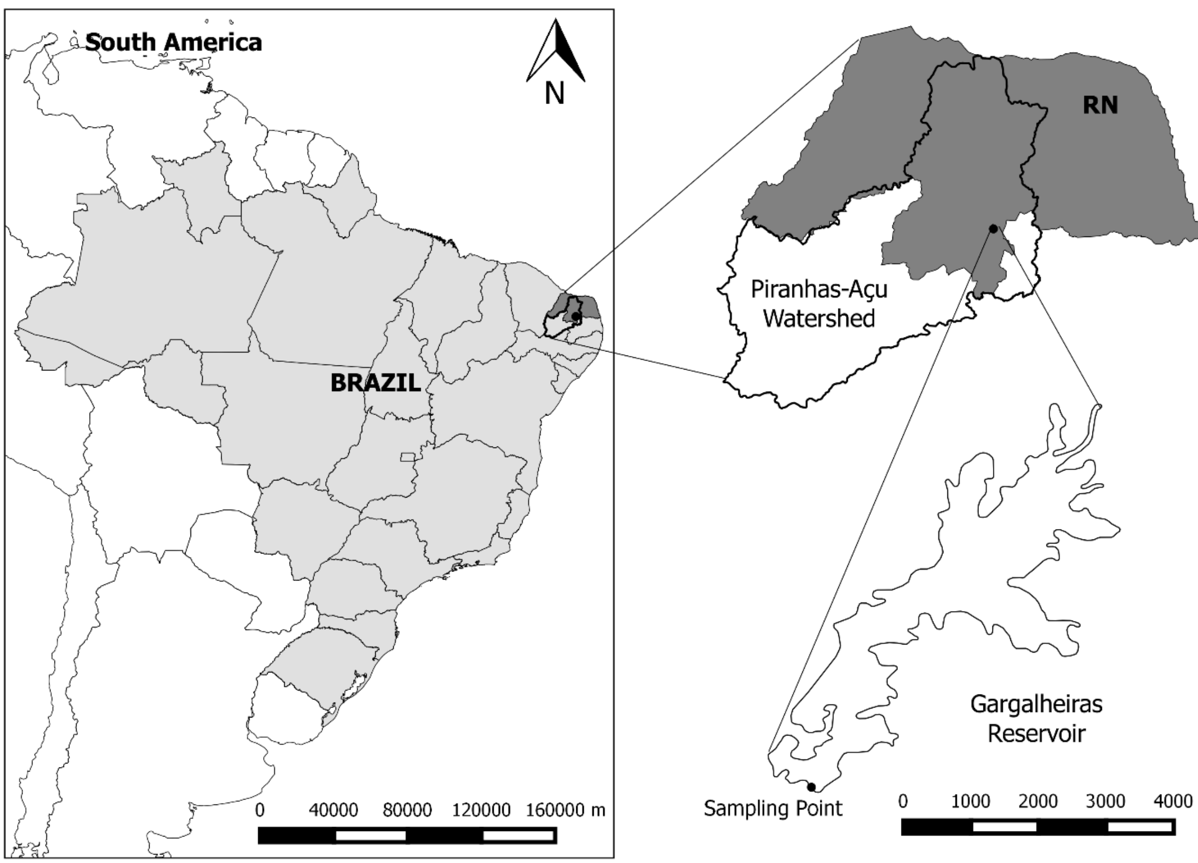

Figure 1: Location of Gargalheiras reservoir and the sampling point, in northeastern Brazil

Sampling and pre-treatment

Water and sediment for the experiment were collected at the same sampling point (Fig. 1) using a van Dorn sampler and manual Kajac corer (50 cm long, 7 cm diameter), respectively. The sediment collection (0-10 cm) occurred near to the dam, due to the low volume presented by the reservoirs, which contained only approximately 1% of their maximum volume, drastically reducing the surface area at that time. The sampling point is also near the catchment outputs at which all the surface runoff converges and there are, thus, crucial points for the accumulation of sediments. The samples were stored in polyethylene clear containers and transported in a thermally insulated box with ice. Sediment and water were kept refrigerated until beginning of the experiment.

Overlying water characteristics

At the laboratory, the natural water was characterized by measuring pH, DO, temperature, soluble reactive phosphorus concentration (SRP) and total dissolved phosphorus concentration (TDP). Then, the water was filtered in 1.2 µm microfiber glass membrane for removal of suspended particles. The filtered water was kept refrigerated until the beginning of experiment. The general features and chemical concentrations in the overlying water used in the experiments were presented in Table 1. Both natural and deionized water were slightly acid to neutral (Table 1). They were also kept at the same temperature. While the deionized water had high dissolved oxygen content and nutrient absence, the eutrophic water from Gargalheiras had low dissolved oxygen concentration and high phosphorus content.

Table 1: Brief description of the overlying water used in the experiment

Parameters	Deionized	Eutrophic
pH	5.28	6.08
DO (mg L^{-1})	7.8	3.9
T (°C)	26.4	26.2
SRP (µg L^{-1})	0	225.6
TDP (µg L^{-1})	0	184.4

Experimental design

The experiment intended to address if oxygen scarcity interferes on phosphorus releasing under different overlying water concentration of P. Different oxygen concentrations (low and high oxygen) were simulated for natural eutrophic and deionized overlying water. Deionized water was used to simulate the highest potential of release of P and natural water from Gargalheiras to simulate a eutrophic ambient. The experiment was carried out in 12 microcosms. The treatments were: low oxygen eutrophic; low oxygen deionized; high oxygen eutrophic; and high oxygen deionized. Each treatment had 3 replicates.

The tests were performed in amber bottles with 500 g of sediment and 1 liter of overlying water. The first 10 cm of the collected sediment were homogenized, weighted and placed into each bottle. The water was slowly added along the bottle wall, so the artificial disturbance at the sediment-water interface was minimized. The oxygen scarcity was simulated by blowing N_2 into the overlying water until hypoxic conditions, and then those bottles were kept closed. For those treatments simulating high oxygen concentration, bottles were kept open.

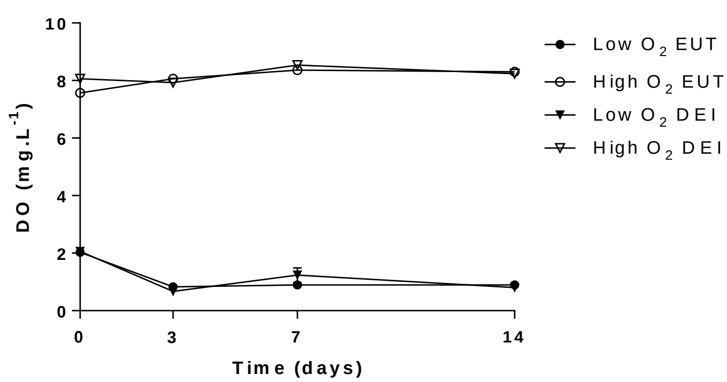

Figure 2: Dissolved oxygen concentrations during the experiment. Treatments: Low O_2 EUT = hipoxic eutrophic conditions; High O_2 EUT = oxic eutrophic conditions; Low O_2 DEI = hipoxic oligotrophic conditions; High O_2 DEI: oxic oligotrophic conditions.

Dissolved oxygen concentration oscillated varied little (7.5 to 8.8 mg/L) in high oxygen treatments. In the low oxygen treatments, the DO was kept below 2.0 mg/L during all experiment (hypoxia conditions) (Fig. 2).

SRP and TDP concentrations were measured right after pouring the overlying water and then measured 3, 7, and 14 days later. The P release rate of sediments (flux) F_i was calculated using the following formula (Schaanning et al., 2006):

$$F_i = \frac{(C_t - C_0).V}{A.t}$$

Where F_i is the release rate [μg/(m² d)], i represents the period; C_t and C_0 are the phosphorus concentration at certain time t, 0 (initial) [mg/L]; V is the volume of the overlying water of the system; A is the contact area of the sediment-water interface [m²]; and t is the experiment time [d].

Analytical methods

pH was measured with a proper probe by Digital Instruments, model 1002PH. An electrochemical dissolved oxygen (DO) sensor by Instrutherm, model MO-900 was used to measure the DO concentration, as well as the temperature. SRP concentration in the overlying water was determined using the molybdenum blue method following Murphy and Riley, (1962). The total dissolved phosphorus (TDP) was determined following the simultaneous persulphate oxidation method described by Valderrama (1981) and Murphy and Riley (1962). Dissolved organic phosphorus (DOP) concentration was calculated by subtracting SRP concentrations from TDP concentrations.

Statistical analysis

Variations in results are reported as the standard error of mean (±SD) (n = 3). To identify the effect of hypoxia or P concentration (categorical factors) in overlying water on P release rates (dependent variable), we performed an analysis of variance (two-way ANOVA). All statistical analyses of the data obtained were conducted using STATISTICA software.

Results

P cumulative concentrations

P concentrations in overlying water varied differently at different incubation conditions throughout the entire test period (Fig. 3). We observed that the cumulative P released from the sediments reached the highest concentrations mostly at the seventh (7th) day of the experiment.

Then, at the subsequent studied period, the cumulative P phosphorus concentration tended to decrease. We can also observe that the highest P concentrations were obtained within the low O_2 treatments. Compared with the eutrophic overlying water sediments (Fig. 3a and 3b), the deionized water treatments showed higher cumulative release of P, with peak at the fourteenth day (Fig. 3c and 3d). We can also observe that SRP concentrations are considerably higher than DOP concentrations, but they followed roughly the same tendency towards the cumulative P release, increasing in the first seven days, and then decreasing in the last seven days.

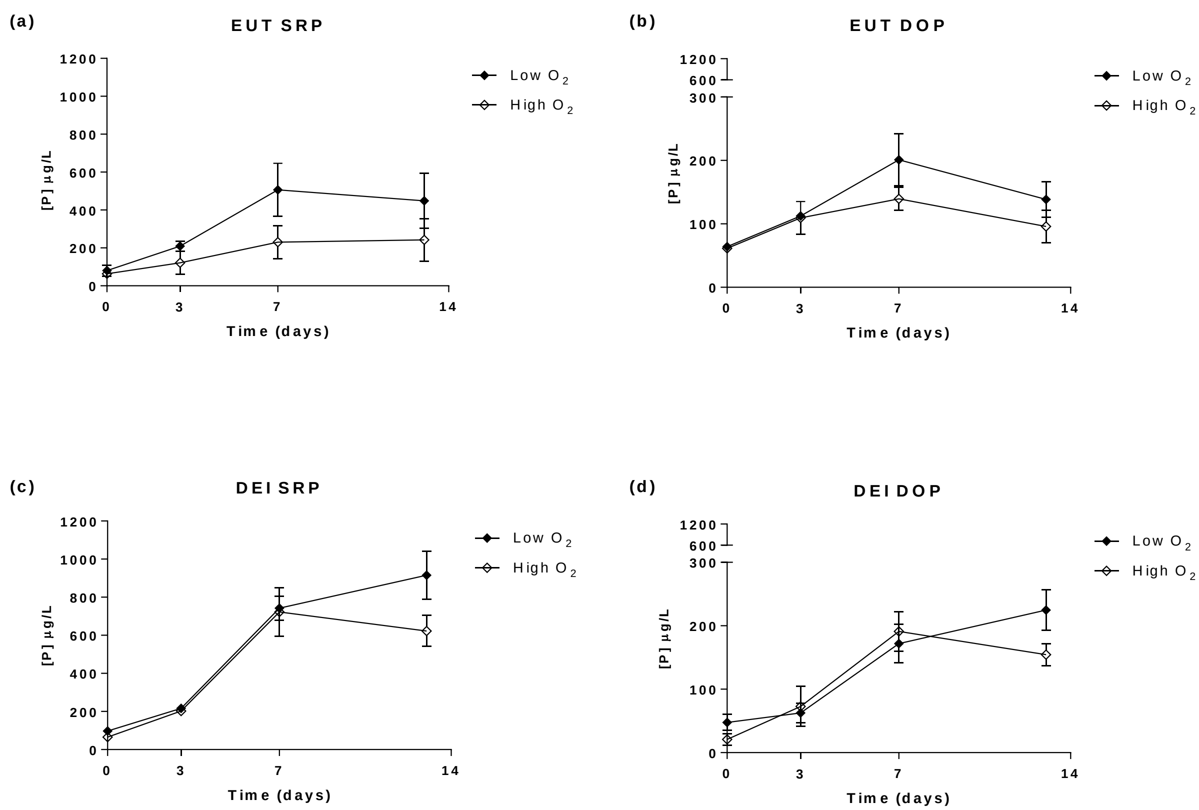

Figure 3: Temporal variation in the cumulative soluble reactive phosphorus (SRP) and dissolved organic phosphorus (DOP) release at sediment-water interface. **(a), (b)** Changes in SRP and DOP under eutrophic conditions. **(c), (d)** Changes in SRP and DOP with deionized overlying water. P gradient: DEI = deionized water; EUT = natural eutrophic water.

All treatments presented the same tendency of pH change (Fig. 4), hitting an average value at the third day (7.23 ± 0.24) of the tests for all treatments, with little further changes.

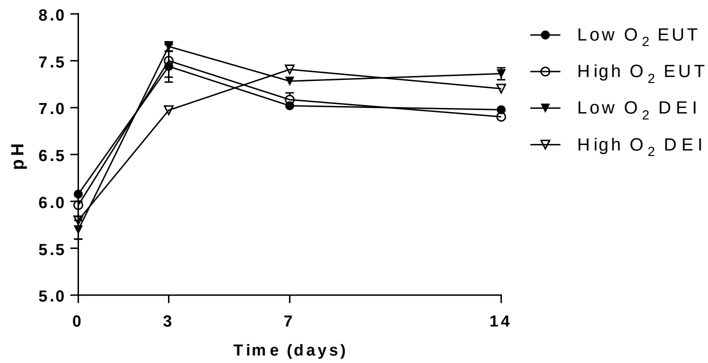

Figure 4: pH in the overlying water with time. Treatments: Low O_2 EUT = hipoxic eutrophic conditions; High O_2 EUT = oxic eutrophic conditions; Low O_2 DEI = hipoxic oligotrophic conditions; High O_2 DEI: oxic oligotrophic conditions.

The experiment was run at room temperature, which oscillated between 26.1 and 21.8ºC (Fig.5).

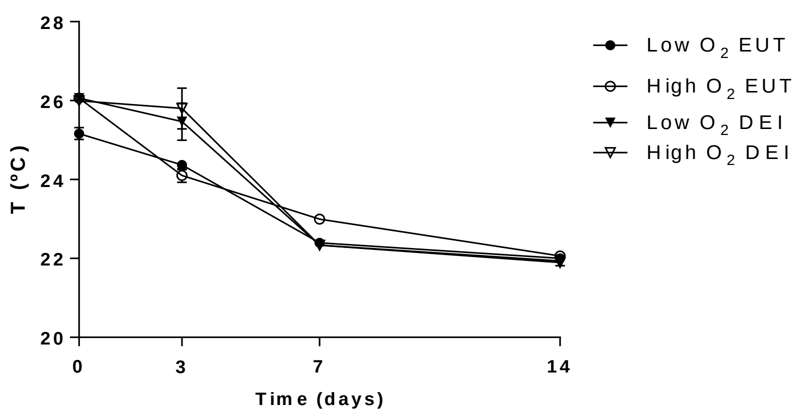

Figure 5: Temperature throughout the experiment. Treatments: Low O_2 EUT = hipoxic eutrophic conditions; High O_2 EUT = oxic eutrophic conditions; Low O_2 DEI = hipoxic oligotrophic conditions; High O_2 DEI: oxic oligotrophic conditions.

Changes in P release rates in different time intervals

Over the 14-day incubation, sediment of all treatments had positive fluxes, with SRP fluxes ranging from 0.59 to 4.5 mg m^{-2} day^{-1} and DOP fluxes, from 0.006 to 1.4 mg m^{-2} day^{-1} (Fig. 6).

Throughout the experiment (0-14 day interval), both P concentrations (*P*=0.0005) and oxygen conditions (*P*=0.0149) had significant effect on SRP fluxes. The same happened for DOP fluxes, where P concentrations (*P*=0.001) and oxygen conditions (*P*=0.0220) were significant as well. Hence, low phosphorus concentration in overlying water tends to favor P releasing for both SRP and DOP fluxes, mostly in oxygen scarcity (Fig. 7).

Due to the peak of the cumulative concentrations observed at the seventh day of the test for nearly all treatments, we analyzed the P fluxes within different time intervals: 0-7 and 7-14. We observed that the P fluxes from the first seven days were always positive for all treatments, indicating P release from sediments (Fig. 6). The fluxes from the subsequent time interval of incubation (7-14) were mostly negative, which is indicative of P uptake by sediments.

During the first seven days, it was observed that the P concentrations had significant effect on SRP fluxes (*P*=0.0006), while oxygen conditions had none. For DOP fluxes, none of the two main effects (P concentrations and oxygen conditions) were significant, although there was significant interaction effect between them (*P*=0.0293). Thus, deionized overlying water favored inorganic-P release at the first seven days of experiment, especially in oxygen absence (Fig. 8a), while organic P release was favored with higher rates in high oxygen conditions (Fig. 8b).

From the 7th day to the 14th, oxygen presence showed significant effect on SRP fluxes (*P*=0.0328); and it was also observed a significant interaction effect between the two categorical factors (*P*=0.0024). For DOP fluxes, P concentration had significant effect (*P*=0.0193) and there was significant interaction effect (*P*=0.0315). Therefore, inorganic-P retention is greater in oxygen presence (Fig. 8c), whereas DOP fluxes are more influenced by P concentration.

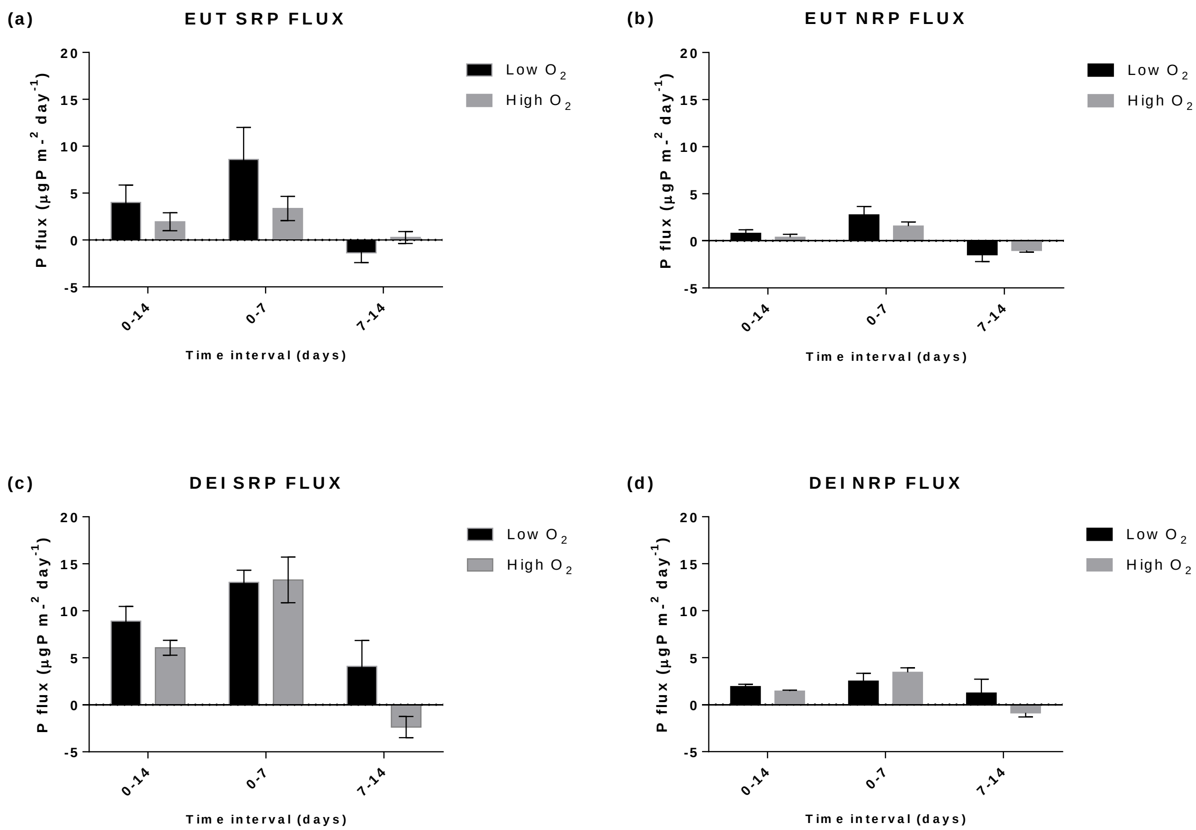

Figure 6: Soluble reactive phosphorus (SRP) and dissolved organic phosphorus (DOP) for deionized and eutrophic overlying water at the different time intervals. Phosphorus concentration: DEI = deionized water; EUT = natural eutrophic water.

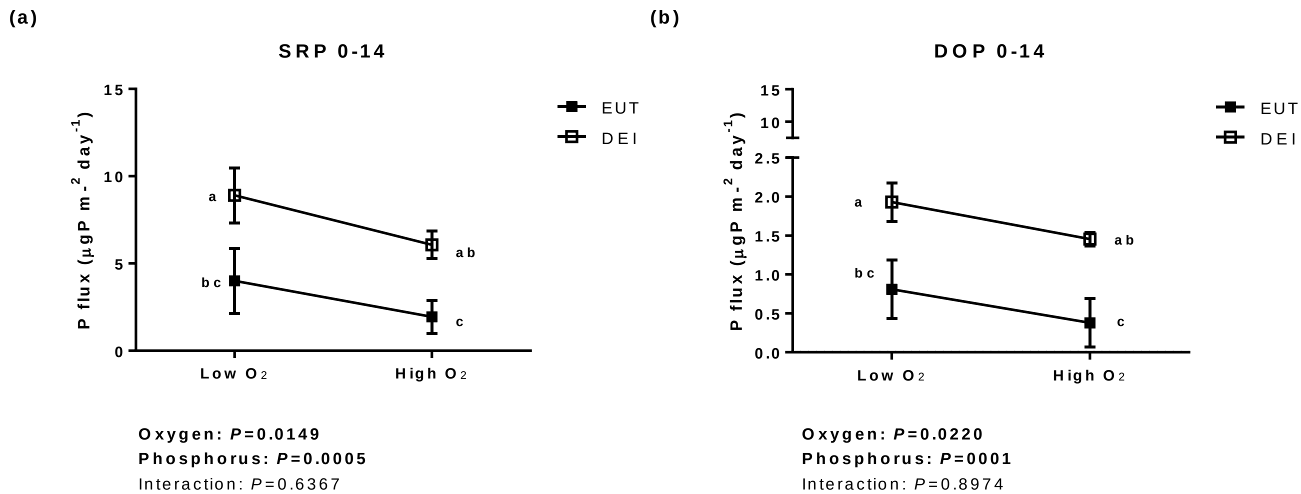

Figure 7: Mean values (± 1SD) of soluble reactive phosphorus (SRP) and dissolved organic phosphorus (DOP) fluxes of the whole experiment time (14 days). Open squares represent treatments with deionized overlying water, while black squares represent treatments with eutrophic overlying water. Results of the p-values of the two-way ANOVA are shown on the bottom of each panel. Significant values ($p<0.05$) are in bold. Phosphorus concentration: DEI = deionized water; EUT = natural eutrophic water.

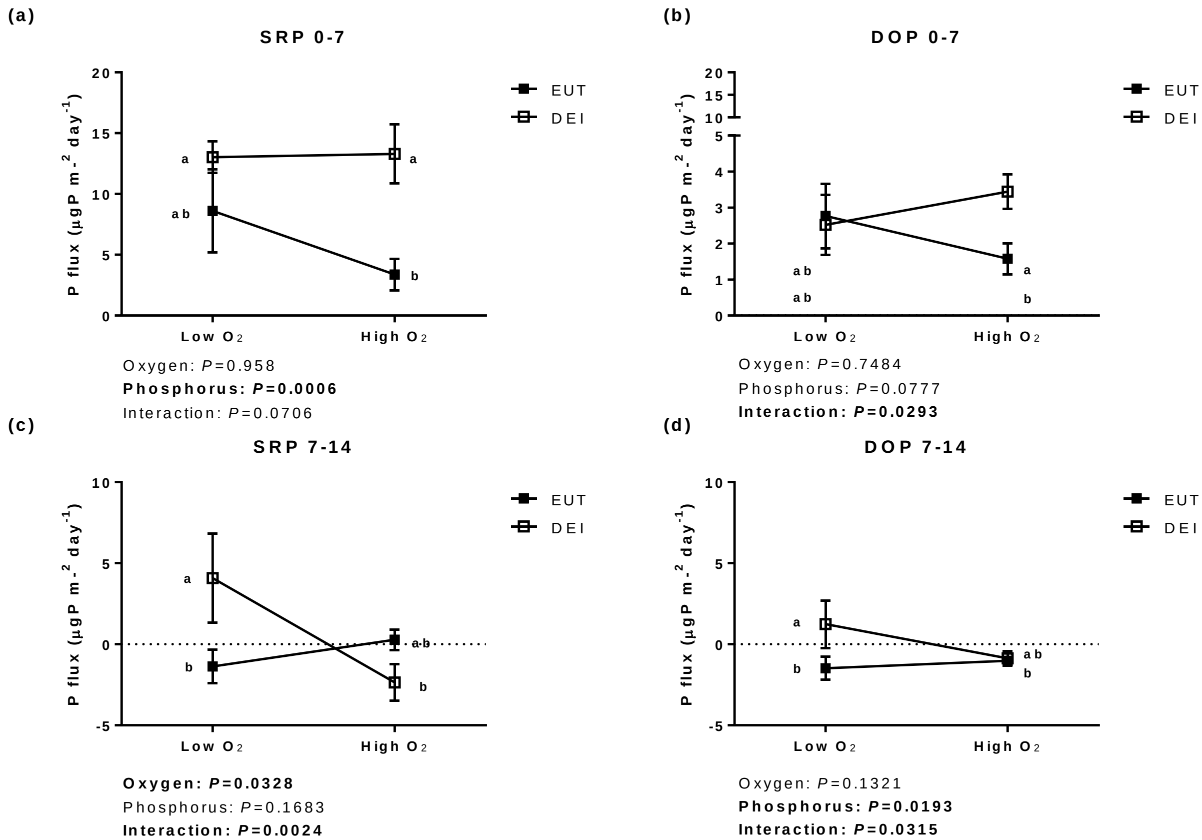

Figure 8: Mean values (± 1SD) of soluble reactive phosphorus (SRP) and dissolved organic phosphorus (DOP) fluxes s of 0-7 days (a,b) and 7-14 days (c,d) intervals. Open squares represent treatments with deionized overlying water, while black squares represent treatments with eutrophic overlying water. Results of the p-values of the two-way ANOVA are shown on the bottom of each panel. Significant values ($p<0.05$) are in bold. Phosphorus concentration: DEI = deionized water; EUT = natural eutrophic water.

Discussion

The current study found that P concentration of overlying water is a key factor that influences P fluxes, mostly in hipoxic conditions. Lower phosphorus concentration in overlying water favors inorganic-P release from sediment. Oxygen conditions also influence the P flux, mostly because, in low oxygen concentration, inorganic-P fluxes are generally higher.

The highest P fluxes were found with deionized overlying water at the first seven days of experiment. That may be due to the different P concentration gradient between a highly P containing sediment with overlying water without P. As the content of mobile P of surface sediments is an indirect predictive factor of internal P release, P gradient simulated had induced higher P release in those treatments (Ramm and Scheps, 1997; Rydin, 2000). Because of the P gradient concentration effect, the P fluxes calculated for the fourteen days of experiment were significantly higher for deionized water, than eutrophic conditions.

The difference between high O_2 and low O_2 SRP release in natural water throughout the experiment suggests to the classic higher release under lower O_2 concentration due to reduction of Fe(OOH)≈P complex (Hupfer and Lewandowski, 2008; Mortimer, 1941). Many previous studies have been pointing out evidence towards this release mechanism (Bates and Neafus, 1980; Holdren and Armstrong, 1980; Jan et al., 2015; Tammeorg et al., 2017), although there is no experimental evidence for it (Golterman, 2001). The sediment surface (10 cm) of Gargalheiras reservoir has a total P pool of 3603.96 mg kg^{-1}, with a mobile P fraction ranging from 29 to 59% with depth. The P fraction bound to Fe was the greatest, despite the variation among the depths (Cavalcante et al., 2018b). Therefore, the Fe(OOH)≈P fraction might have been a significant contributor to SRP release. Also, as P bound to calcium was found to be the second lowest of all P fractions (Cavalcante et al., 2018b), organic P may also have been dissolved in the newly added water, particularly in absence of Ca^{2+} (Golterman, 2004) and it contributed to DOP release.

The beginning of the study (0 to 7 days interval) was characterized by P release in all treatments (positive flux). pH of all treatments were ranging between 5.5 and 6.0 (Fig. 5). These values are considered low, comparing to the ordinary range of 6.5 to 8.5 of natural lakes (Zhang et al., 2016). Acidic conditions are bound to be more effective for greater P release rates, which might have helped to increase the earlier release of P. However, pH tends to neutral along the experiment course, what may have contributed to the P retention later (Kim et al., 2003).

From the 7th to the 14th day of experiment, we detected a decay of P concentration in overlying water which may occur due to the decreasing of temperature along the days (Fig. 2). Temperature is a crucial factor for the increasing of P release because of increasing of the solubility product of some insoluble compounds, lessen of P adsorption capacity and increasing of microbial activities, leading to higher metabolism of organic compounds (Gächter and Meyer, 1993; Jensen and Andersen, 1992; Jeppesen et al., 2007; Kim et al., 2003; Søndergaard et al., 2013; Wu et al., 2014).

Greater DOP fluxes found within the oligotrophic simulated conditions and this may be due to bacteria activity that not only produces soluble phosphates, but can also contribute with refractory organic-P compounds mostly in oligotrophic lakes (Gächter and Meyer, 1993). Poly-P bacterial release also could have taken place, as DOP fraction also includes this kind of phosphate (Golterman, 2001).

Concerning the magnitude of the fluxes found with this study, we could presume that our P fluxes for natural overlying water reached sometimes values ten times higher for SRP fluxes and equivalent values for DOP fluxes in a study carried out for Erhai Lake (EH) in China. The lake is in early stage of eutrophication and presented SRP average flux of 0.18 ± 0.11 mg $m^{-2}day^{-1}$and DOP average flux equals 1.09 ± 0.46 mg/(m^2.d) (Liu et al., 2015). Their cumulative SRP release were also much lower than ours, suggesting that Gargalheiras' sediment is more likely to reach higher P fluxes due to its large total P pool in sediment (Cavalcante et al., 2018b). Values with the same magnitude for cumulative SRP and DOP release of Gargalheiras' sediment were found in a P release study with resuspension of sediments of Yue Lake in China, considered a hypereutrophic urban lake (Wang et al., 2009). This fact may be an indicative that P release concentrations in our study may be underestimated due to the lack of considering physical factors that could contribute to a higher release (Wang et al., 2009).

The results found in this study are very relevant to understanding the patterns of phosphorus release in reservoirs of semiarid regions, where natural conditions are likely to contribute with higher P fluxes. Highly eutrophic reservoirs such as Gargalheiras, which has a large P pool available to release (Cavalcante et al., 2018a), may have its eutrophication issues intensified due to the anoxic sediment. However, the rainy period that contributes to diminish P concentration in overlying water may not help reducing P release, as the P release may happen even if oligotrophic conditions are found in overlying water due to P concentration gradient (Cavalcante et al., 2018a; Golterman, 2004).

Conclusions

In Brazilian semiarid regions, represented by Gargalheiras reservoir, P release is influenced by eutrophic state of overlying water and oxygen conditions of sediment. Due to its natural conditions, such as high temperature and pH, low depth and elevated evaporation rates, semiarid reservoirs can concentrate large amounts of phosphorus, contributing to algal blooms and the oxygen depletion of its sediments. Our study has proven that anoxic sediments are likely to release more phosphorus than the high oxygen ones. Therefore, water quality may suffer even more degradation in drought periods. Even if the rainy periods come to dilute the P present in overlying water making it oligotrophic, we found that P pool in sediments are sufficiently high to release P by difference of gradient concentration. Hence, sediment P pool may contribute to elevate P concentrations enough to bring back the algal blooms and anoxic conditions of sediment.

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