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Longitudinal gradient in limnological variables in the Upper Paraná River: a brief description and the importance of undammed tributaries

Gradiente longitudinal de variáveis limnológicas no Alto Rio Paraná: Breve descrição e importância dos tributários não barrados

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Abstract: Aim: Describe the limnological pattern in a longitudinal gradient in the Paraná River, a highly dammed river, in a stretch localized between two dams, but rich in undammed tributaries. **Methods:** Twelve transects in the longitudinal gradient of the Paraná River were sampled, with the first transect being placed right after Porto Primavera dam, and the last one in the lotic region of the Itaipu dam. In each of these transects, water transparency, electrical conductivity, pH, total nitrogen and total phosphorous were analyzed. **Results:** In those regions nearer Porto Primavera dam it was observed high values of water transparency and low values of nitrogen and phosphorous. The values of water transparency decreased and the values of nitrogen and phosphorous increased as the distance from Porto Primavera dam increased. Because the new tributaries connect to the Paraná River, with the sites farer from Porto Primavera dam presenting values similar to those prior its construction. **Conclusions:** Increase in the nutrients concentration and changes in ecological integrity are probably due to the presence of the undammed tributaries. They are originate in different river basins and therefore contribute to the Paraná River in distinct manners. Results presented here are an indicative of the fundamental importance of undammed tributaries in mitigating damming negative impacts in extremely dammed rivers and highlight the importance of keeping such tributaries free of dams.

Keywords: reservoir impact; oligotrophication; Porto Primavera; nutrient retention; floodplain.

Resumo: Objetivo: Descrever variações limnológicas em um gradiente longitudinal do rio Paraná, rio com grande numero de barragens, ao longo do trecho entre Porto Primavera e Itaipu, região com inúmeros tributários não barrados. **Métodos:** Foram analisados 12 transectos ao longo do eixo longitudinal do rio Paraná, distribuídos desde a jusante do reservatório de Porto Primavera até a montante do reservatório de Itaipu. As variáveis limnológicas analisadas foram: transparência da água, condutividade elétrica, pH, fósforo e nitrogênio totais. **Resultados:** Nas regiões mais próximas a Porto Primavera observou-se altos valores de transparência da água e baixas concentrações de nitrogênio e fósforo. Em geral, foi observado incremento nas concentrações de nitrogênio e fósforo ao longo do gradiente longitudinal do rio Paraná, com redução na transparência da água à medida que os tributários se conectavam com a calha do rio Paraná. Nos pontos mais distantes da barragem de Porto Primavera, observaram-se valores de nutrientes próximos aqueles reportados antes da construção dessa barragem. **Conclusões:** O aumento de nutrientes observados e, consequentes, alterações na integridade ecológica, provavelmente devem-se à presença de tributários não barrados que, por originarem-se de bacias hidrográficas diferentes, contribuem de maneira distinta na composição limnológica do rio Paraná. Os resultados obtidos nesse estudo apontam que tributários não barrados possuem importância fundamental na preservação das condições ecológicas necessárias para manutenção da biota no rio Paraná e podem mitigar impactos gerados pela barragem de Porto Primavera, ressaltando a importância desses tributários na conservação da produtividade do rio.

Palavras-chave: impacto de reservatórios; oligotrofização; Porto Primavera; retenção de nutrientes; planície de inundação.

1. Introduction

The River Continuum Concept (RCC) predicts that there is a continuous longitudinal gradient in the physico-chemical variables within a river system, and that this gradient results in a series of responses within the natural communities (Vannote et al., 1980; Sedell et al., 1989). The construction of reservoirs disrupts the river flow and modifies the longitudinal gradient pattern, reducing the concentration of nutrients downstream the reservoirs (Friedl & Wüest, 2002; Agostinho et al., 2008), what affect the water quality and all biological communities present (Rădoane & Rădoane, 2005; Ouyang et al., 2011). The negative effects of the construction of reservoirs, mainly those connected to sediment deposition, are potentialized in a cascade of reservoirs (when several reservoirs are sequentially constructed in the same river; Agostinho et al., 2008). The, the retention of sediments in a cascade of reservoirs can reach values higher than 80% of the total sediment, consequently reducing organic matter and nutrients, leading to an oligotrophic state (Barbosa et al., 1999; Straskraba, 1990; Vörösmarty et al., 2003).

Reservoirs are subjected to distinct effects of physical, chemical and biological components of their tributaries (Torloni, 1994). The different communities' spatial composition variation, are results of the discharge of different tributaries, with distinct environmental conditions that promote a high diversity of habitats (Tundisi, 1999; Mwedzi et al., 2016; Portinho et al., 2016). Then, tributaries are important contributors of nutrients, suspended solids and organic/inorganic matter to another river (Portinho et al., 2016). In those cases, in which a higher order river is dammed, the presence of undammed tributaries can contribute to the conservation of natural conditions downstream the reservoir (Rice et al., 2001).

Damming negative impacts can be even higher if the reservoirs are formed upstream floodplain regions (Kingsford, 2000). The retention of sediments upstream the floodplain can change the sedimentation and erosion processes into the floodplain (Roberto et al., 2009), increasing erosive capacity of the river downstream of the reservoirs (Kummu et al., 2004) and changing the flooding regime (Fantin-Cruz et al., 2016). In the south Brazilian region, the construction of dams is one of the major human impacts in natural aquatic environments (Poff et al., 1997; Stanford & Ward, 2001; Agostinho et al., 2008; Souza-Filho, 2009), mainly due to flow control and oligotrophication, as a result of reduced phosphorous concentrations and increased water transparency (Roberto et al., 2009). In turn, decreases in planktonic species diversity and abundance are being observed in reservoirs such as Porto Primavera dam, located in the Upper Paraná River (Bonecker et al., 2009; Rodrigues et al., 2009; Bovo-Scomparin et al., 2013).

In the Paraná River several dams are built in cascade, changing the natural process of the river by the retention of sediments in each upstream reservoir (Agostinho et al., 2004b). In turn, the Paraná River has become extremely oligotrophic (Roberto et al., 2009). However, in the region of the Upper Paraná River, downstream Porto Primavera and upstream Itaipu dams, a stretch of 230 km long is, until now, free of dams. In this stretch, several tributaries discharge in the Paraná River and contribute to organic and inorganic matter increase. Additionally, most of these tributaries are undammed and originated from distinct river basins with distinct land use. Thus, here we evaluate the variation in limnological variables along the Paraná River channel in this stretch, more specifically, we aimed to describe the limnological variables along the Paraná River longitudinal gradient and its tributaries. It is expected that, as undammed tributaries can contribute with nutrients along the river channel, the negative effects of damming in the water quality, represented by limnological variables, will be reduced as more tributaries discharge reach the Paraná River channel.

2. Methods

The study area is located in the Upper Paraná River between Porto Primavera dam and Itaipu reservoir (22°37'S 53°6'W and 24°03'S 54°15'W). Samplings were performed quarterly (from August 2013 to May 2015). The sampling in the Paraná River occurred in both margins (right and left) and in the central point of the river (called distances D), totaling 12 along the longitudinal axis of the Paraná River. The distances were distributed in order to obtain sampling sites without influence of tributaries and sampling sites with greater influence (Figure 1).

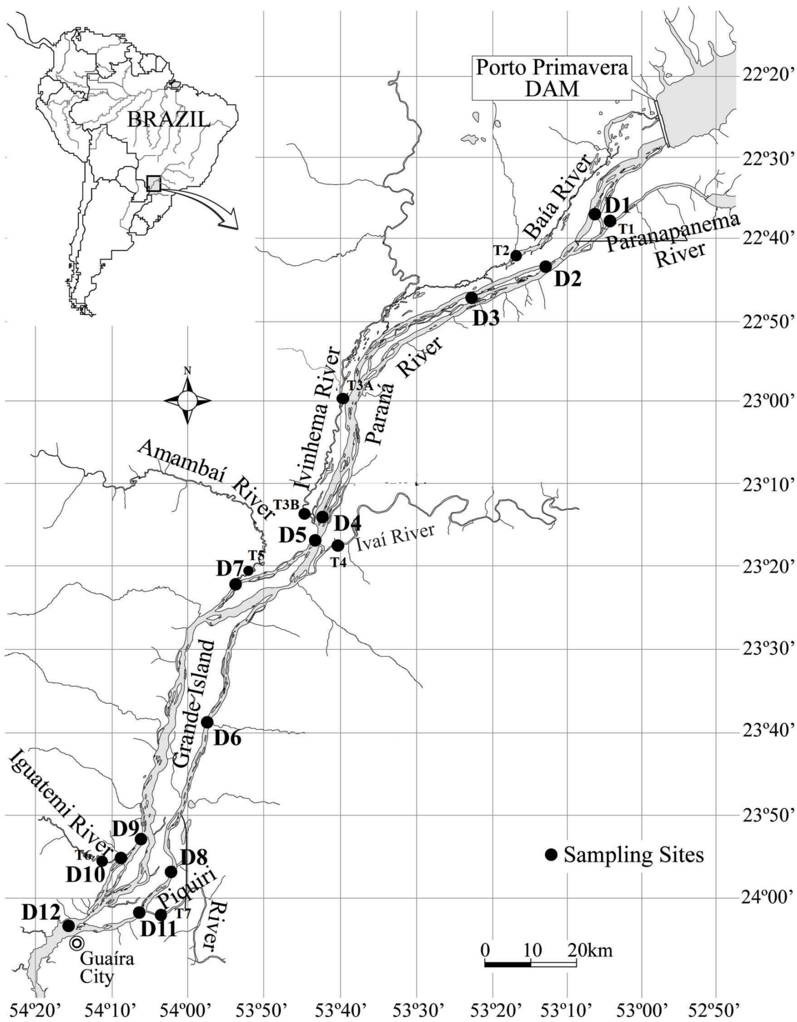

Figure 1. Sampling sites in the Upper Paraná River considering different distances from the Porto Primavera dam and its tributaries. D1=Porto Primavera dam; D2=Paranapanema River mouth; D3=Baía River mouth; D4 and D5=Ivinhema River mouth; D6=Ivaí River mouth; D7=Amambaí River mouth; D8 and D9=right and left channel, respectively, of Ilha Grande; D10=Iguatemi River mouth; D11=Piquiri River mouth and D12=upstream Itaipu reservoir. T1= Paranapanema River; T2= Baia River; T3A and T3B= Ivinhema River; T4= Ivaí River; T5= Amambai River; T6= Iguatemi River and T7= Piquiri River. Samplings were performed in the 12 segments in right and left margins and in the center of the river channel. The tributaries: T1= Paranapanema River; T2= Baia River; T3A and T3B = Ivinhema River; T4= Ivaí River; T5= Amambai River; T6= Iguatemi River and T7= Piquiri River.

Seven tributaries in this stretch of the Upper Paraná River were considered, three of them located in the left margin (Paranapanema (T1), Ivaí (T4) and Piquirí (T7) rivers) and four in the right margin (Baía (T2), Ivinhema (T3A and T3B), Amambaí (T5) and Iguatemi (T6) rivers). The tributaries located on the left margin are longer, ranging in length from 400 to 600 km and have springs in crystalline rocks. The tributaries of the right margin do not extend 400 km in length and are headspring in the sedimentary basin of the Paraná river, in the mountains of Maracaju and Caiapó (Stevaux, 2000).

From all of these seven tributaries, only the Paranapanema River presents dams in its course, the others, of free flow, have darker waters, with higher contents of suspended solids. For all of the tributaries one sampling site was included upstream of the confluence with Paraná River, with exception of the Ivinhema River, in which two junctions were sampled (T3A and T3B). The samples were taken in the opposite direction of the water flow of the Paraná River to avoid sample dependency

In each sampled site, we evaluated the water transparency by Secchi disk depth (Secchi - m), pH, electrical conductivity (Condutivity - μScm^{-1}), total phosphorous (TP- μL^{-1}), and total nitrogen (TN- μL^{-1}). Surface water samples were obtained using a Van Dorn bottle conditioned in ice and transported to the laboratory, where they were analyzed for total phosphorus and total nitrogen. Processing methodologies for total nitrogen and total phosphorous followed Mackereth et al. (1978) and Bergamin et al. (1978), respectively.

In order to detect possible longitudinal patterns in the limnological variables of the studied stretch of the Paraná River, a Principal Components Analysis (PCA) was applied to the data. The Principal Components Analysis (PCA) was also used to detect possible patterns in the tributaries limnological composition. Both PCAs were followed by an Analysis of Variance (Anova) in order to test the significance of the ordination axis (dependent variables). In the first case, we considered the distance of Porto Primavera dam and the sampled region (using score of PCA of distances of Porto Primavera dam and categorizing according to the region sampled: right and left margin and river channel; explanatory variables) and in the second case, with each tributary (explanatory variable).

Additionally, the analysis of variance (ANOVA) was applied to verify changes along the longitudinal axis of the Paraná river in the variables sampled (pH, electrical conductivity, Secchi depth, total nitrogen and total phosphorus) (dependent variables) in relation to distance of Porto Primavera dam and the sampled region. The *post hoc* Tukey HSD was applied to the data when significant interactions were detected. Only water transparency, total phosphorous and nitrogen were considered for such tests (dependent variables). This is because these variables are the most representative of environmental productivity (e.g., Schindler, 1974; Smith et al., 2006; Marois et al., 2015). Data was log transformed (except pH) in order to achieve tests. Analyses were performed in the software R (R Core Team, 2015) and graphics built in the software Statistica 7.1 (StatSoft, 2005).

3. Results

The two first axes of the PCA, applied to the limnological variables of the Paraná River, explained 67.9% of the total variability (PCA 1, with 44.4% of explanation of data variability and PCA 2, with 23.5%). Significant interaction between margin and distance from Porto Primavera dam were observed in the ANOVA applied to the first PCA axis (Anova: $F_{22,222}$=6.71, p<0.001) while, for the second axis significant values for distance and margin were observed (Anova: Distance: F_{11}=2.26, p=0.01; Margin: F_{2}=3.59, p=0.02). The variables that most influenced positively the ordination were, for the first axis, electrical conductivity, and, negatively total phosphorous. The second PCA axis was influenced positively by water transparency (Secchi disk depth), and negatively by total nitrogen (Figure 2). A longitudinal increment in total phosphorous and nitrogen along the Paraná River was observed, especially in relation to the first PCA axis. The *post hoc* Tukey HSD test detected no differences among distance one to three (D1 to D3), however significant differences were detected among these initial distances and the intermediate distances (D4 to D9), as well as among the initial distances and the more distant sites (D10 to D12).

A reduction trend in the values of Secchi disk depth and pH was observed along the longitudinal gradient of the Paraná River. Total phosphorous also varied along the river gradient, nevertheless, with increases in their concentrations along the Paraná River. Additionally, in the sampling site D9 increased water transparency and decreased total nitrogen and phosphorous was observed, being

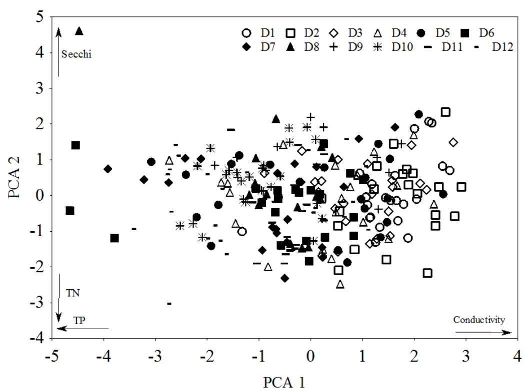

Figure 2. Ordenation of limnological variables from the Upper Paraná River in relation to the distance from Porto Primavera dam represented by the two firsts axes of the Principal Components Analysis, highlighting the variables that most influenced the ordination.

more pronounced in the right margin (Figure 3). The limnological variables (pH, Secchi disk depth and total phosphorous) presented similar pattern among the distances, with D1 to D3 differing from the distances D4 to D12.

The first two axes of the Principal Components Analysis explained 69.9% of total variance found in the tributaries limnological data (PCA 1, with 42.9% of explanation of data variability and PCA 2, with 27.0%), highlighted three groups of tributaries and were most influence by Secchi disk depth, electrical conductivity, pH and total phosphorous. The first PCA axis presented significant differences among the tributaries (Anova: F=69.17, p<0.001) and separated the Paranapanema (T1) and Ivaí rivers (T4) from the Ivinhema (T3A and

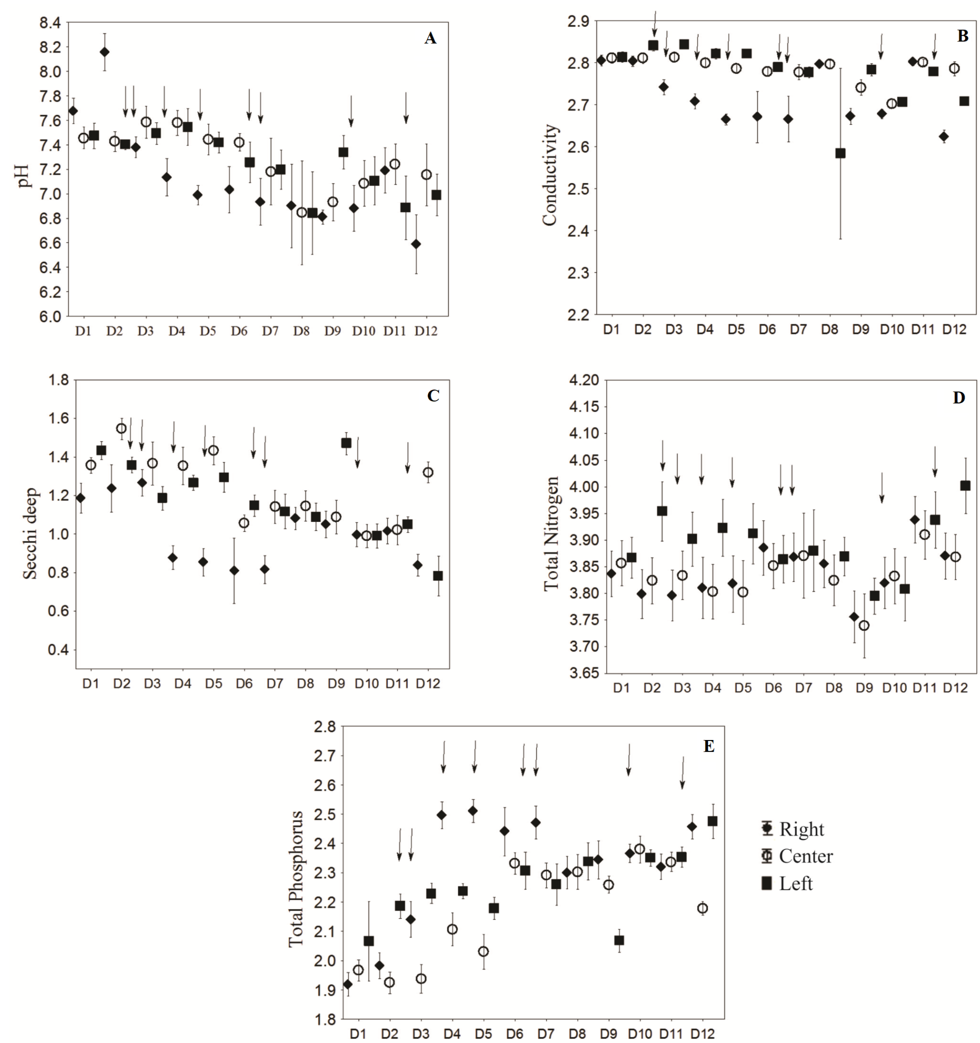

Figure 3. Mean and standard error of pH (A), electrical conductivity (B), Secchi disk depth (C), total nitrogen (D) and total phosphorous (E) in the Upper Paraná River between Porto Primavera and Itaipu dams, considering distance from Porto Primavera dam (D1 to D12) and river margin (right, center and left). Values are log transformed (except pH). Arrows point the junction of a tributary in the Paraná River.

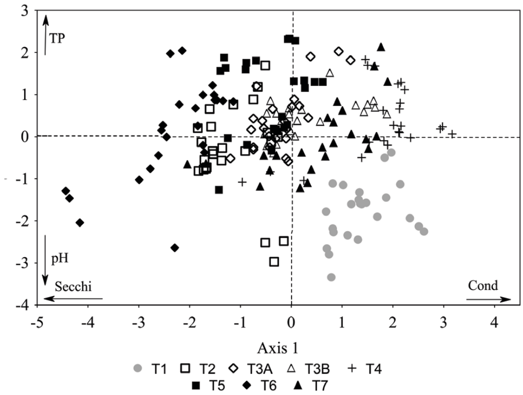

Figure 4. Ordination of limnological variables from the Paraná River tributaries in relation to the distance from Porto Primavera dam, highlighting the variables that most influenced the ordination Conductivity=electrical conductivity, Secchi=Secchi disk depth (water transparency), TP=total phosphorus and pH.

T3B), Amambaí (T5) and Piquiri (T7) rivers. On the second PCA axis the Paranapanema River was significant different from the other rivers (Anova: F=20.68, p<0.001; Tukey<0.001).

Different patterns were observed for each of the tributaries. The Paranapanema River (T1), the closest tributary to Porto Primavera dam, presented the highest values of Secchi disk depth and the lowest values of electrical conductivity, pH and total nitrogen of all the seven tributaries (Figure 4). The tributaries that presented the lowest values of Secchi disk depth were the Amambaí and Iguatemi Rivers (T5 and T6, respectively) (Figure 5), both in the right margin of the Paraná River. Additionally, the Iguatemi River (T6), presented the highest concentrations of total nitrogen and total phosphorous, followed by the Ivinhema River (T3A and T3B) and the Amambaí River (T5).

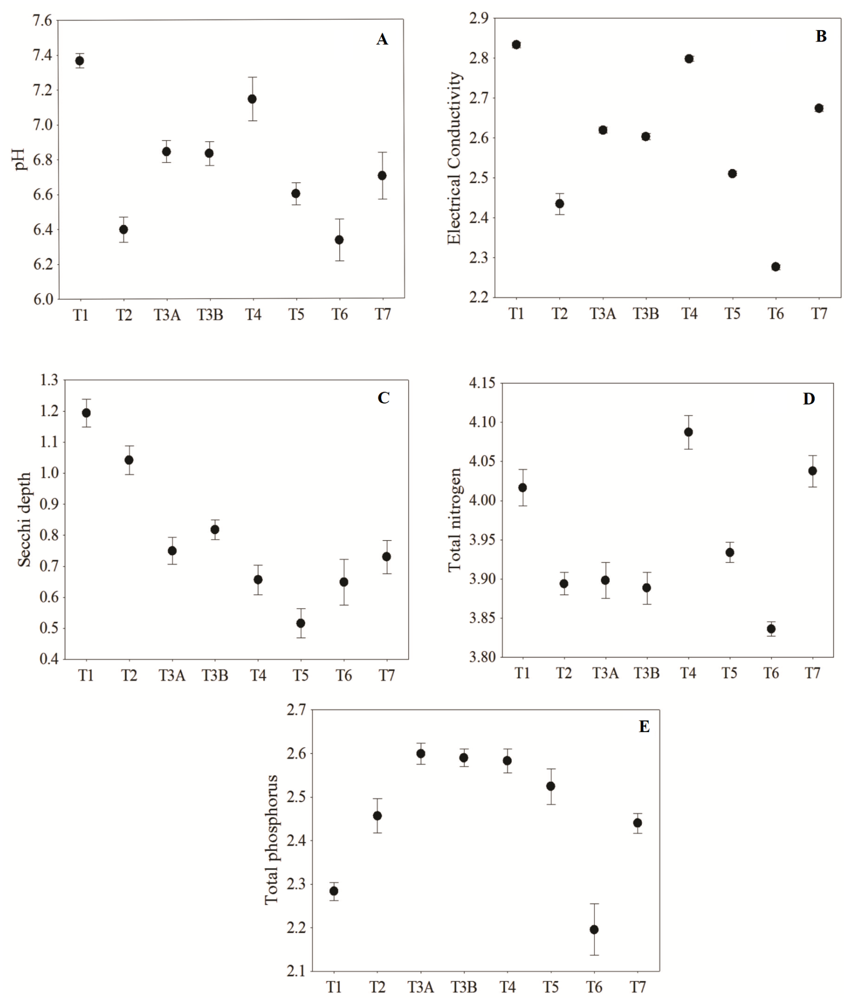

Figure 5. Mean and standard error of pH (A), electrical conductivity (B), Secchi disk depth (C), total nitrogen (D) and total phosphorous (E) in the Paraná River tributaries between Porto Primavera and Itaipu dams. T1=Paranapanema River; T2=Baía River; T3A and T3B=Ivinhema River; T4=Ivaí River; T5=Amambaí River; T6=Iguatemi River; T7=Piquiri River. Values are log transformed (except pH). Vertical bars=Standard error.

4. Discussion

The river tributaries provide, among other modifications, the increase of nutrients (Vannote et al., 1980), fundamental for the maintenance of the integrity of these ecosystems. The studied region suffers great influence of upstream reservoirs, especially from Porto Primavera dam (Montanher & Souza Filho, 2015), that retains more than 70% of the Paraná river total phosphorous (Roberto et al., 2009). Decreases in nutrient concentrations caused by dams barring the river course are widespread in the world and reported in several studies (Kummu & Varis, 2007; Fu et al., 2008; Ouyang et al., 2011; Arias et al., 2014). The low values of total phosphorous and nitrogen and the high values of Secchi disk depth observed in those sites closest to Porto Primavera dam are in accordance to the general trend observed worldwide, indicating that Porto Primavera dam is indeed acting as a sink of environmental nutrients. As observed by Thomaz et al. (2009) and Mormul et al. (2012) an alarming issue of the observed oligotrophication process, is that, by promoting increases in the water transparency, submerged aquatic macrophytes are able to develop and alter the planktonic community and also to facilitate the introduction of visual predators that will compete and predate native species (Fugi et al., 2008; Pereira et al., 2015), producing cascade effects on the trophic food webs (Harris et al., 2005).

In those sites more distant from Porto Primavera dam, higher nutrient concentrations (total nitrogen and phosphorous) and lower values of Secchi disk depth were observed, possibly due to increments in the amount o suspended solids in the water column, as it is expected in a natural fluvial gradient mainly from the marginal erosion caused by the river flow (Vannote et al., 1980). The increment in the physical-chemical variables in this study with the distance from the dam is an indicative that the negative effects of damming are reduced with increasing distance from it, with such effect being more pronounced in the total nitrogen and phosphorous, the most important nutrients in limiting biological productivity (e.g., Schindler, 1974; Marois et al., 2015).

Longitudinally, in the Paraná River, sites located near Porto Primavera dam presented distinct limnological configuration to those located near Itaipu reservoir. These differences in the limnological configuration can be assigned to the discharge of the tributaries in the Paraná River, some tributaries presenting high values of nutrients, as nitrogen and phosphorous, which are higher than those from the Paraná River. Therefore, the high inputs of nutrients from tributaries will increase primary production and probably reduce the Paraná River erosion capacity as more tributaries connect to the river channel and the distance from the dam increases, what could decrease some negative impacts of damming (Fu et al., 2008). It must be highlighted that the reduction of the negative impacts, mainly sediment retention, of the Porto Primavera dam may not be assigned to a single tributary. These tributaries originate from different river basins, then the contribution of each tributary will differ and their downstream effects will be cumulative as more tributaries connect to the Paraná River channel. This fact is highlighted by the high concentration of phosphorous in the last transect before the Itaipu reservoir, which presented similar concentrations to those observed prior to Porto Primavera damming (Roberto et al., 2009).

Despite the fact that tributaries can increase the nutrient concentrations and river water turbidity, reaching water conditions more similar to those observed in natural environments, it is important to notice that the conditions observed prior to damming are unlikely to be reached or restored without the removal of the dam (Montanher & Souza-Filho, 2015). This fact is due to the volume of water carried by the Paraná River being greater than those of its tributaries, which can cause dilution of these nutrients. In the studied environment, Montanher & Souza-Filho (2015) presents data of suspended solids before dams (1970s), which reached an average of 40 mg L^{-1}. Those values are higher than those we can obtain currently (average of 10 mg L^{-1}), but it is clear in our study that values of suspended solids are greater far from the dam after the tributaries reach the Paraná River channel.

The construction of dams creates several negative impacts in the natural environment and it seems that the presence of undammed tributaries downstream the dam can sustain some ecological integrity in the dammed river (Affonso et al., 2015). However, despite the growing evidence of negative impacts of dam construction and the importance of keeping undammed tributaries, several projects for dam construction in dammed or undammed rivers are already approved or being proposed, as it is the case of the Ivaí and Piquiri Rivers, both undammed rivers (Affonso et al., 2015). The Paranapanema River, the only dammed tributary, presented the highest values of water transparency and the lowest values of total phosphorous, contributing less than the other tributaries to the recovery of the natural configuration of the analyzed stretch. The nutrient concentration of the Paranapanema River is an indicative of sediment retention upstream dams, and it is expected that, if the other tributaries are dammed such as Ivaí and Piquiri Rivers, their nutrient configuration will be similar to the dammed Paranapanema River and, consequently, their contribution to the maintenance of the Paraná River ecological integrity will be severely limited.

The region of the Upper Paraná River floodplain, in which the study was conducted, is a conservation unit that allows the persistence of a great diversity of native fauna and flora, including some endemic or endangered species (Agostinho et al., 2004a, b). This region can be the last stretch of the Paraná River free of dams, however, it still depends of the functioning of the upstream environments and the nutrients provided by them, as presented in this study. There is a limited environmental degradation that such region can support and, if this limit is override, that is, without the nutrients to sustain the biota provided by the tributaries, irreversible alterations in the floodplain and in the Paraná River will certainly occur, leading most of the region's threatened species closer to extinction risk.

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