Acta Limnologica Brasiliensia

Publication of the Brazilian Association of Limnology

Original Article

Acta Limnologica Brasiliensia, 2016, vol. 28, e26

http://dx.doi.org/10.1590/S2179-975X5516

ISSN 0102-6712

Fluvial lateral environments in Río de La Plata basin: effects of hydropower damming and eutrophication

Ambientes fluviais laterais na bacia do Rio da Prata: efeitos dos barramentos de hidrelétricas e da eutrofização

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Cite as: Debastiani Júnior, J.R. et al. Fluvial lateral environments in Río de La Plata basin: effects of hydropower damming and eutrophication. *Acta Limnologica Brasiliensia*, 2016, vol. 28, e26.

Abstract: Aim: Identify large-scale limnological patterns in lateral water bodies of Río de La Plata Basin, considering the influence of river damming and urban conglomerates. **Methods:** Samplings were performed in a broad spatial scale (along 16 latitude degrees) during two seasonal periods (23 sites in summer and 20 sites in winter) for measurements of physical and chemical variables, chlorophyll *a* and periphyton biomass. **Results:** Geographical distance between sites was significantly correlated with the environmental dissimilarity (Euclidean distance). Reservoir and floodplain associated sites exhibited lower phosphorus concentration. Eutrophic conditions were higher in sites close to urban areas and regions with intensive agriculture and livestock activities, which exhibited higher conductivity, concentration of nitrogen and chlorophyll *a*. Sites associated to reservoirs had higher periphyton biomass. Inorganic suspended matter was higher in summer whereas organic suspended matter was higher in the winter, due to contrasting rain seasonality in the upper Paraná River sub-basin. No significant correlation between the dissimilarity of the vegetation and the environmental dissimilarity or geographical distance between sites was observed. **Conclusions:** The limnological conditions in the fluvial lateral habitats in the Río de La Plata basin are highly influenced by reservoirs construction, intensive urban occupation and rain seasonality.

Keywords: river dams; wetland; water quality; limnological variables; human impact.

Resumo: Objetivo: Identificar padrões espaciais em larga escala na limnologia dos corpos d'água laterais da bacia do Rio da Prata, considerando a presença dos barramentos e conglomerados urbanos. **Métodos:** Amostragens foram feitas em uma ampla escala espacial (ao longo de 16 graus de latitude) durante dois períodos sazonais (23 locais no verão e 20 no inverno) para medições de variáveis físicas e químicas, clorofila *a* e biomassa do perifiton. **Resultados:** A distância geográfica entre os locais foi significativamente correlacionada com a dissimilaridade ambiental (distância Euclidiana). Locais associados a reservatórios e planícies de inundação apresentaram menores concentrações de fósforo. Condições mais eutróficas estiveram associadas a áreas urbanas e regiões com atividades agropecuárias intensivas, como maior condutividade, concentrações de nitrogênio e clorofila *a*. Maior biomassa de perifiton ocorreu em locais sob influência de reservatórios. Material particulado inorgânico foi maior no verão e orgânico no inverno, devido à contrastante sazonalidade das chuvas na porção superior da bacia do rio Paraná. Não houve correlação significativa entre a dissimilaridade da vegetação e a dissimilaridade ambiental ou distância geográfica entre os locais amostrados. **Conclusões:** As condições limnológicas nos ambientes fluviais laterais da bacia do Rio da Prata são altamente influenciadas pela construção de reservatórios, intensa ocupação urbana e sazonalidade na precipitação.

Palavras-chave: barragens; áreas úmidas; qualidade da água; variáveis limnológicas; impacto humano.

1. Introduction

The entire set of human activities in a hydrographic basin is considered as part of a socio-ecological system (Redman et al., 2004). Alterations in the rivers flow regime and impacts of the different land uses change the natural characteristics of the water bodies by disruption of functional patterns (Ward & Stanford, 1995; Agostinho et al., 2007; Ohl et al., 2007; Silva et al., 2012). A direct consequence is the re-structuration of the aquatic communities (e.g. José de Paggi & Devercelli, 2011 – for microzooplankton; Callisto et al., 2005 and Katano et al., 2009 – for benthic macroinvertebrates and Ferrareze et al., 2014a – for fish).

The Río de La Plata basin represents one of the most important socio-ecological systems in South America. It is the second largest basin in the continent, following the Amazonian, and is the fifth in the world (Cuya et al., 2013). The landscape is dominated by huge fluvial systems (Paraná, Paraguay and Uruguay Rivers), direct or partially connected to a mosaic of other aquatic and semi aquatic lateral environments, and also exhibits a marked latitudinal variation in terms of climate (Peel et al., 2007).

Adjacent water bodies, such as marginal lakes and floodplains, strongly interact with the typical rivers longitudinal patterns (Ward, 1989). These lateral environments have a significant influence in the fauna and flora biological cycles, both in free-flowing (Junk et al., 2014) and regulated (Ward & Stanford, 1995) systems. They commonly have an intensive growth of aquatic vegetation, resulting in high amount of organic detritus. Such characteristics result in a remarkable limnological distinctiveness compared to the main river courses (Thomaz et al., 2007; Granado & Henry, 2012, Ferrareze et al., 2014b).

In the last years, important academic and governmental initiatives focused on proper characterization and classification of the regional South America continental wetlands (Kandus et al., 2008; Junk et al., 2014; Lasso et al., 2014).

In case of La Plata basin an important aspect to be considered in the environmental studies is related to the intense human interference. In the northeast region, for instance, were is located the State of São Paulo, the most populous and economically developed in Brazil, only 17% of the domestic sewage was treated before discharge into the rivers in the 2000's (Martinelli et al., 2002). Even in areas were depuration plants for urban effluents have been installed, the streams and rivers still transport significant loads of nitrogen, phosphorus and sediments (Oliveira et al., 2014). Besides urban impacts, the intensive agriculture and livestock, as well as the sequences of hydropower dams in the upper Paraná sub-basin, result in significant impacts for the aquatic ecosystems (Agostinho et al., 2007; Nogueira et al., 2012).

In this context we selected for investigation a large set of lateral environments, all of them colonized by aquatic macrophytes, which are connected to the main rivers and reservoirs of La Plata basin and distributed along a wide latitudinal gradient (16 latitude degrees – about 3.000 Km lengthy).

The aim of the study was to discriminate regional limnological patterns in lateral fluvial habitats, related to their geographical positioning in the basin, the dominant macrophyte and degree of human interference. It was hypothesized that: (1) the limnological characteristics would be highly influenced by local human interference, despite of geographic proximity (distance among sites), and (2) similar macrophyte assemblages would result in similar limnological characteristics. We expect the results to be useful for the ecological understanding of wetlands structure and functioning as well as for definition of regional conservation strategies.

2. Material and Methods

2.1. Study area

The Río de La Plata basin ranges from approximately 14°S to 34°S. It is composed by three main rivers: Paraná, Paraguay and Uruguay, all with a north-south predominant orientation. Covering an area of 3.17 x 10^6 km^2 (Bazán & Arraga, 1993), it drains part of Argentina, Bolivia, Brazil, Paraguay and Uruguay territories. The main drainage systems were originated in the Jurassic – Cretaceous (ca. 202 M.Y.A.), during the separation of South American and African continents (Stevaux et al., 2004). The mean flow of the basin is 22,000$m^3.s^{-1}$, 17,000m^3 from the Paraná River (after confluence with Paraguay River) and 5,000m^3 from the Uruguay River (Cuya et al., 2013).

The Paraná River is the tenth in the world in water discharge, with a total length of 4,695 km and a watershed of 2.8 x 10^6 km^2. The river and its tributaries are highly influenced by anthropogenic impacts. Towards north, this sub-basin concentrates 50% of Brazilian population and have 146 hydropower reservoirs with dams over ten meters high (Agostinho et al., 2007; Cuya et al., 2013).

The Paraguay River is 2,621 km long, receiving in its right margin important Andean tributaries, such as Pylcomayo and Bermejo. This river has some sinuous stretches and very large floodplain areas (*Pantanal*) with low flow (Domitrovic, 2002; Poi de Neiff, 2003; Fortney et al., 2004; Frutos et al., 2006). The Paraguay River is free from the presence of large artificial reservoirs.

The Uruguay River has a total length of 1,770 km and its watershed covers 38.5 x 10^4 km^2. In the upper stretches, the river channel runs in deep vales with one of the highest hydro-electrical potential in the world (40.5 $KW.km^{-2}$), but due to the marked absence of lateral water bodies and floodplains, this superior region was not sampled.

The sampling design covered a wide spatial scale, considering the longitudinal gradients of the main tributaries (upstream → mouth) and the latitudinal gradients along the main sub-basins. Twenty three lateral water bodies were sampled in summer/2010, but 20 in winter/2010, as 3 sites along Uruguay River were dried in the second campaign. Twelve sites were directly associated to reservoirs and 11 directly to free lotic stretches (Figure 1, Table 1); all sites were shallow (maximum 2.6 m of depth) and represent lateral lakes or bays colonized by the macrophytes with wide connection to the main water body (river ecosystem).

2.2. Environmental variables

The water temperature (WT), total dissolved solids (TDS), dissolved oxygen (DO), pH and electrical conductivity (K) were measured with an Eureka Manta 2 water probe in three zones of each studied site: inside the macrophyte stands

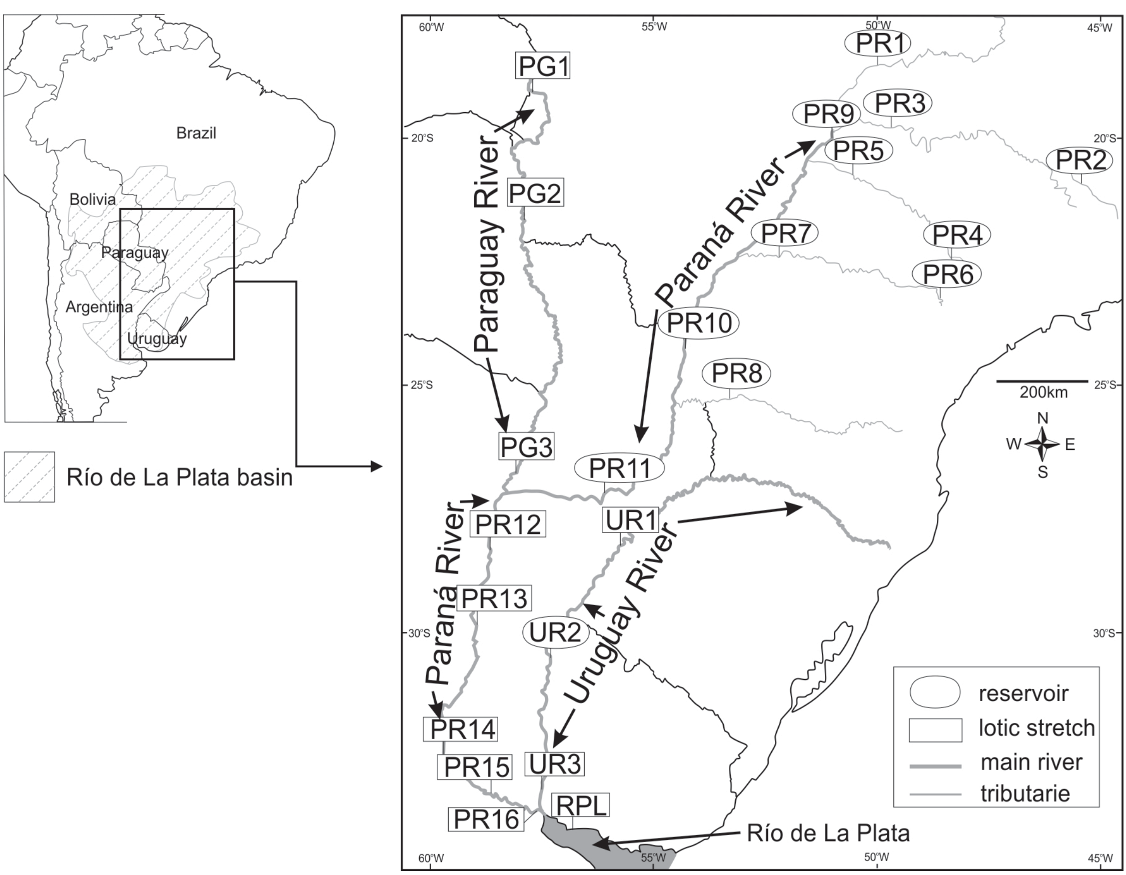

Figure 1. Study area and sampling sites in the Río de La Plata basin (for codes and descriptions see Table 1).

Table 1. Sampling sites codes, kind of the associated main water body, hydrographic sub-basin and geographical coordinates.

Site	Sub-Basin	Main water body	Coordinates	
PR1	Upper Paraná River Basin	Reservoirs	18°42'23.59"S	50°02'28.25"W
PR2			20°58'39.97"S	45°31'33.05"W
PR3			19°56'51.47"S	49°44'51.51"W
PR4			22°41'03.74"S	48°22'00.77"W
PR5			20°55'34.36"S	50°34'33.65"W
PR6			23°28'23.66"S	48°38'23.56"W
PR7			22°38'02.87"S	52°09'39.88"W
PR8			25°30'30.60"S	53°17'34.35"W
PR9			20°11'42.10"S	50°59'04.82"W
PR10			24°29'57.44"S	54°17'51.79"W
PR11	Middle Paraná River Basin	River	27°26'20.04"S	56°14'30.16"W
PR12			28°29'33.95"S	59°02'24.47"W
PR13			30°00'54.59"S	59°32'51.93"W
PR14	Low Paraná River Basin	River	32°44'07.16"S	60°43'10.12"W
PR15			33°40'49.00"S	59°38'48.80"W
PR16			33°56'49.45"S	58°27'07.47"W
PG1	Paraguay River Basin	River	18°58'48.29"S	57°38'26.26"W
PG2			21°40'41.13"S	57°53'25.21"W
PG3			26°52'10.45"S	58°19'54.12"W
UR1	Uruguay River Basin	River	28°29'35.23"S	55°58'17.53"W
UR2		Reservoir	30°44'57.60"S	57°44'37.31"W
UR3		River	33°49'40.48"S	58°25'41.52"W
RPL	Río de La Plata	River	34°25'38.85"S	57°34'40.75"W

(macrophyte zone), approximately at 1m distance from the macrophyte stands (adjacent zone) and in the limnetic zone (minimum of 10 m apart from macrophytes). From the set of data obtained in each zone a mean value for each variable (at least 10 measures) was calculated. Transparency (SD:Z) was measured in the adjacent zone based on Secchi disk depth and transformed to percentage of total depth. One water sample was collected in the adjacent zone of each site to quantify the inorganic and organic amount of suspended matter (ISM and OSM, respectively) (Cole, 1979), turbidity (MS Tecnopon table turbidimeter), nitrogen and phosphorus concentrations (Strickland & Parsons, 1960; Mackereth et al., 1978; Valderrama, 1981) and Chlorophyll *a* (filtering through Millipore AP40 filter and extraction in 90% cold acetone). Three fragments (mainly stems) of the dominant macrophyte of each site were collected for periphyton quantification (scraping of the periphyton, filtering through Millipore AP40 filter and extraction in 90% cold acetone).

The phyto-physiognomy (dominant species and approximate percent of coverage area of the ecological groups – submerged, emergent rooted and free floating) was determined *in situ* and by the analysis of standardized photos sequences taken during fieldwork (Table 2). This characterization was

Table 2. Coverage percentage of the main types of macrophytes in each sampling site during summer. Estimations based on *in situ* observation and standardized photo sequences analysis.

	Submerged	Emergent Rooted	Free floating
PR1	0	100	0
PR2	0	0	100
PR3	0	80	20
PR9	50	15	35
PR4	0	50	50
PR5	90	0	10
PR6	0	75	25
PR7	0	0	100
PR10	0	50	50
PR8	0	100	0
PR11	0	100	0
PR12	0	80	20
PR13	0	0	100
PR14	0	100	0
PR15	0	50	50
PR16	0	90	10
PG1	0	0	100
PG2	0	50	50
PG3	0	0	100
UR1	0	100	0
UR2	100	0	0
UR3	0	100	0
RPL	0	100	0

performed only in summer due to the macrophytes senescence in several sites during winter.

A principal component analysis (PCA) based on the variables mentioned before (for water probe measurements means were used), both for summer and winter periods, was applied to ordinate the sampling sites (Euclidean distance method in the PCORD 5.31 software, McCune & Mefford, 2006). The variables were log-transformed (except pH and transparency) and then standardized by standard deviation.

In addition, a Mantel test was applied to determine the correlation of the geographical distance between sites and the environmental dissimilarity between sites (Euclidean distance method in the PCORD 5.31 software, McCune & Mefford, 2006). For the summer period, this test was also applied to investigate the correlation of the geographical distance between sites and the phyto-physiognomy dissimilarity between sites and the correlation of the environmental dissimilarity between sites and the phyto-physiognomy dissimilarity (Euclidean distance method in the PCORD 5.31 software, McCune & Mefford, 2006).

3. Results

Differences between sites under influence of reservoirs and the ones associated to free river stretches were evidend. The first were characterized by higher transparency (Figure 2) and periphyton biomass, in this case especialy during winter (Figures 2 and 3). The second were characterized by higher conductivity, total dissolved solids, turbidity, phosphorus concentration (increasing from head to mouth) and suspended matter (Figures 2 and 3).

However, several exceptions for this tendency were observed: Barra Bonita reservoir (PR4, summer and winter), Salto Grande reservoir (UR2, summer, no winter data), São Simão reservoir (PR1, summer), the middle stretch of the Paraná River (PR12 and PR13, summer), Yaciretá reservoir (PR11, winter) and the upper and middle stretches of the Paraguay River (PG1 and PG2, winter) (Figure 2).

The alternation between inorganic and organic suspended matter was observed when compared summer and winter for the entire basin. No longitudinal tendency, from head to mouth, was observed for these variables neither in summer nor winter.

The values of chlorophyll *a* found for the riverine sites were slightly higher than the ones found for the reservoirs both in summer and winter. Nevertheless, São Simão (PR1) and Salto Grande (UR2) reservoirs, in summer, and Barra Bonita (PR4), in winter, showed high concentrations of chlorophyll *a*.

The water temperature did not show high variation among sampling sites during summer, but a pronounced latitudinal effect was observed in winter (Figure 3).

No clear pattern regarding pH and dissolved oxygen could be observed, although they had

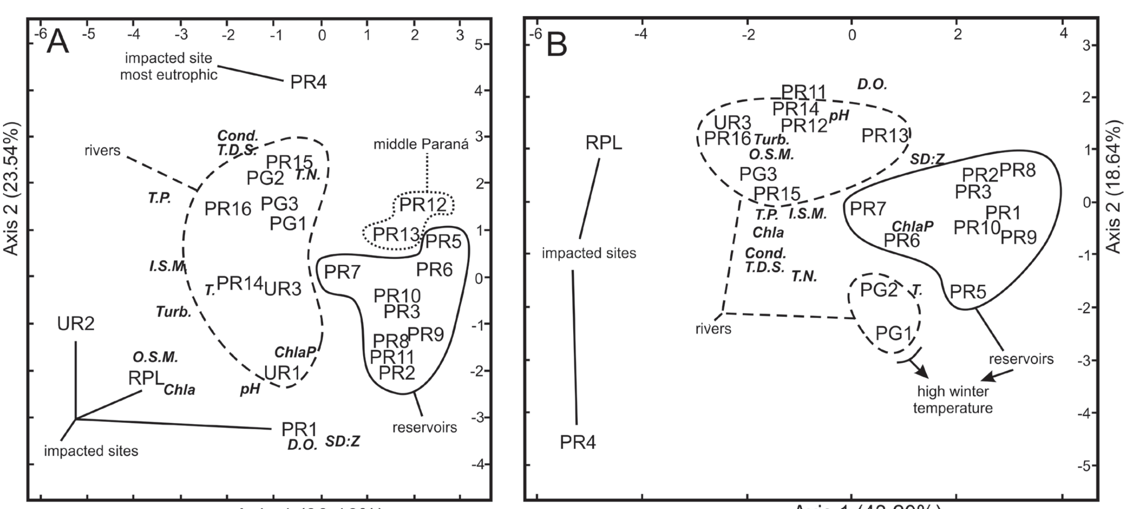

Figure 2. Bi-plot graphs of the PCA analysis performed for summer (A) and winter (B) data. Variables: Cond = conductivity; Chl*a* = chlorophyll *a*; Chl*a*P = periphyton chlorophyll *a*; DO = dissolved oxygen; ISM = inorganic suspended matter; OSM = organic suspended matter; SD:Z = transparency; Turb = turbidity; TN = total nitrogen; TP = total phosphorus; TDS = total dissolved solids; T = water temperature. Sampling sites codes as in Table 1.

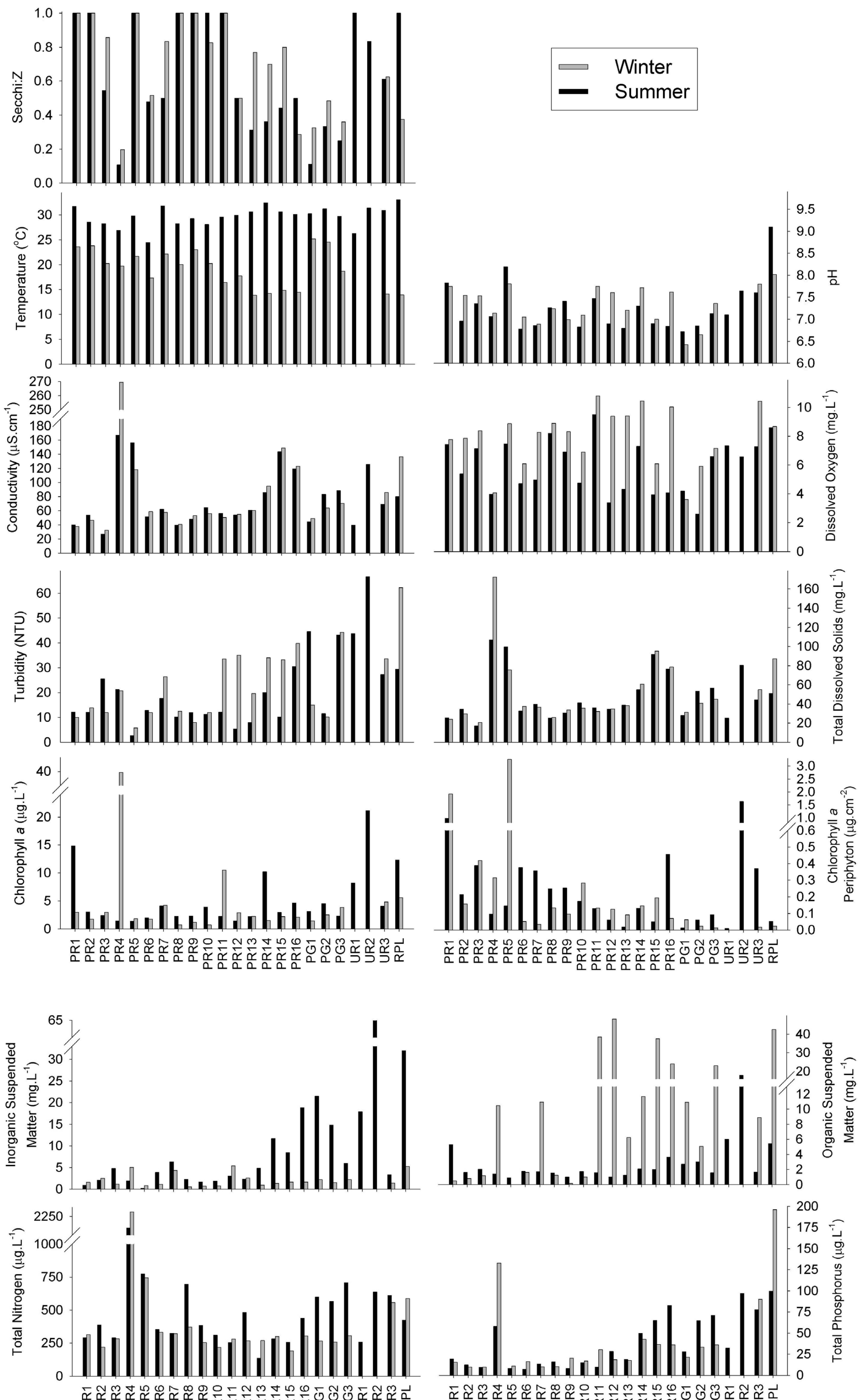

Figure 3. Mean values of the limnological variables in the different sites during winter and summer.

significant positive correlation (r = 0.71 for summer and r = 0.73 for winter, both $p<0.05$).

Higher values of total nitrogen occurred in the Paraguay River sub-basin, with increase from head to mouth in the summer, but the highest values were measured in locally impacted sites, such as Barra Bonita reservoir (PR4) in the Paraná sub-basin. Salto Caxias (PR8), Salto Grande (UR2) and Três Irmãos (PR5) reservoirs also exhibited high values in summer, but in winter only Três Irmãos (PR5) maintained high values, probably due to exportation from Barra Bonita (upstream located). Salto Grande (UR2) could not be sampled in winter.

During summer the sites more locally impacted were São Simão (PR1), Barra Bonita (PR4) and Salto Grande (UR2) reservoirs as well as the lower portion of the La Plata basin, especially the Río de La Plata itself (RPL). São Simão (PR1) and the Río de La Plata (RPL) exhibited higher correlation with chlorophyll. The Río de La Plata (RPL) and Salto Grande (UR2) reservoir were also correlated with high amounts of inorganic suspended matter. Barra Bonita (PR4) reservoir, influenced by loads from São Paulo metropolitan region, was the most nitrogen rich site and with the highest conductivity, and these features determined its positioning in the PCA ordination. The Três Irmãos (PR5) reservoir, also in the Tietê River, but downstream Barra Bonita (PR4) reservoir, had high values of nitrogen and conductivity, but its positioning was closer to the other reservoirs, showing a possible recovery of the river along its course.

The Mantel test, performed to determine the geographical structure of the environmental data, indicated that distance between the sampling sites was significant both in summer (r = 0.15, p = 0.03) and winter (r = 0.35, p = <0.01).

It was also observed trough the Mantel test that the dominance of the different ecological groups of macrophytes were neither correlated with the geographical coordinates (r = -0.0, p = 0.55) nor with the limnological variables measured (r = -0.04, p = 0.54) in the summer period.

4. Discussion

The use of the entire hydrographic basin as the scale of investigation in limnological studies is justified by the fundamental role of the basin structure and processes in determining the characteristics of the water bodies. Nevertheless, samplings in broad spatial scales are usually logistic limited.

The sampling effort employed in the present study intended to provide a synoptic view of this important South America basin, with emphasis in lateral river habitats (bays, lakes) dominated by aquatic macrophytes. With the use of PCA and Mantel Test it was possible to evidence different environmental characteristics and its relations with human activities.

The intensive damming in the upper portion of the Paraná sub-basin results in more transparent (less turbid) water, lower amounts of phosphorus and higher development of periphytic community. These results evidenced the role of reservoirs as sinks for suspended sediments and phosphorus (Thornton, 1990) and corroborated previous studies in the upper Paraná sub-basin in which phosphorus reduction and transparency enhancement were observed (Barbosa et al., 1999; Roberto et al., 2009). The presence of several reservoir cascades contributes to relatively homogeneous conditions of the upper Paraná sub-basin and the transference effects from reservoir to reservoir were previously observed (Nogueira et al., 2012; Silva et al., 2005).

The development of the periphytic community in reservoirs lateral habitats and floodplains is positively influenced by the relative lentic conditions and flow control. In sites associated to free-flowing rivers a lower biomass would be associated to the influence of floods, frequent water level fluctuations and higher turbidity (Uehlinger et al., 2003; Fuller et al., 2011).

The geographical positioning also influenced the characteristics of the studied areas. It was observed an increasing trend from head to mouth for conductivity, total dissolved solids and turbidity in the different studied sub-basins. This indicates the rivers increasing load capacity. Nevertheless, these longitudinal additions were not so evident in the dammed tributaries, indicating once again that reservoirs change the typical rivers ecological processes.

A gradient of resources is expected from the head waters to the mouth of rivers (Vannote et al., 1980). The seasonal flood pulse and associated lateral inputs of material and organisms into the river channel is also a predictable process (Junk et al., 2014; Tockner et al., 2000). Therefore, both longitudinal and lateral interactions are of major importance in determining the characteristics of lotic systems (Ward, 1989; Ward & Stanford, 1995). In the present study the increasing tendency of total dissolved solids and conductivity could be associated to the longitudinal processing of organic matter and its decomposition/mineralization. But the constant high amount of suspended matter would be determined by transport (run-off) from the catchment and floodplains and continuous resuspension by the turbulent water flow (lateral and vertical transport). An intriguing tendency was the alternation between the inorganic and organic matter (suspended solids) from summer to winter, respectively. It is probable that rainfall during the summer, mainly in northern latitudes, carried inorganic matter from the adjacent soils into the water bodies and, during the winter, processes of senescence (mainly of macrophytes) led to higher organic contents in the water.

Another difference was related to the concentration of nutrients, higher in the Paraguay sub-basin in summer and in the low portion of the La Plata basin for both seasons. Geological formation and geomorphological regional differences directly influence the nutrient concentration in the considered sub-basins (e.g. Andean nutrient-rich tributaries in the Paraguay sub-basin). Additionally, the intensive land and water uses in some crowded regions of La Plata basin (e.g. the metropolitan São Paulo in upper Paraná and metropolitan Buenos Aires in low Paraná River) are of major concern in terms of nutrient and hazardous substance inputs. Land use and topography has also been related to nutrient contents in other tropical catchment (Castillo, 2010).

Whereas the reservoirs promote the retention of nutrients, in the free river stretches an increase in the concentration (enhanced from urban and agricultural runoff) is expected. However, this increase was not so evident for the entire Paraná River sub-basin. In the middle part of this sub-basin vast wetlands (such as the Esteros de Iberá, Argentina) can also act as sinks for nutrients. The role of wetlands in nutrient retention/removal is well known (Boavida, 1999), and it is observed for both natural (Greiner & Hershner, 1998; Cohen et al., 2007) and manmade systems (Calheiros et al., 2007; Johannesson et al., 2011). Thus, the presence of significant wetlands in the middle Paraná River stretch attenuates the expected longitudinal downstream increase of nutrient. This fact is corroborated by the statistical association of the middle stretch of the Paraná River sub-basin (PR12 and 13) with upstream reservoirs sites during summer (when the loads would be higher) (PCA analysis). In addition, the nutrient rich water from the Paraguay River is probably diluted by the larger volume of nutrient poor water from the upper Paraná basin (in part due to the effect of dams) after these rivers confluence. The high concentration of nutrients in the low stretch of the Paraná River sub-basin is probably caused by the direct effect of the existing highly urbanized areas (Buenos Aires and other upstream highly urbanized areas), in addition to natural longitudinal increases.

There were sites under strong local impacts, which exhibited particular characteristics (clearly seen in the PCA) such as São Simão (PR1) and Salto Grande (UR2) reservoirs, during summer and Barra Bonita (PR4) and Río de La Plata (RPL) for both seasons. All sites showed eutrophication signals. The Yaciretá (PR11) reservoir, during winter, also had a divergent position in the PCA, but this was a case of biased sampling, due to a strong rain event in the moment of the sampling which caused a sudden raise in the turbidity of the water.

São Simão (PR1) reservoir showed high values of periphytic and planktonic chlorophyll, dissolved oxygen, high amounts of organic suspended matter and phosphorus. The eutrophication of this reservoir is mainly attributed to the agricultural and livestock in its catchment. However, little limnological information is available for this reservoir (Pinto-Coelho et al., 2006).

Barra Bonita (PR4) reservoir is the first large reservoir in the Tietê River, which has in its catchment large cities like São Paulo, with approximately 20 million habitants in its metropolitan region. The reservoir is highly eutrophic and receives constant loads of nutrients from sewage, agriculture and urban runoff (Tundisi & Matsumura-Tundisi, 1990; Tundisi et al., 1991, 1993).

Salto Grande (UR2) reservoir showed a very high amount of suspended matter and nutrients, showing a eutrophic condition, which corroborates with Chalar's (2008) revision of this reservoir limnological features.

The Río de La Plata (RPL) also exhibits high values of suspended matter, nutrients and planktonic chlorophyll, evidencing a tendency of eutrophication in the low part of the basin. Both Paraná River and Uruguay River nutrients and solids concentrations were high in this region, the former due to urban and industrial activities and the last due to exportation of eutrophic waters from Salto Grande reservoir, caused by agricultural runoff and middle size cities (e.g. Uruguaiana, BR; Concordia AR and Salto, UY).

The Upper and Middle Paraguay River statistical association with reservoirs during winter

(PG1 and 2 in the PCA) reflect the latitudinal influence on the temperature - higher values in the northern part of the basin.

The significant positive correlation between the geographical distance and the environmental dissimilarity found trough the Mantel test for both periods reflect the expected variation along a large hydrographic basin. Closer sites would exhibit characteristics that are more similar. Nevertheless, the correlation index was low. This can be explained by the high geographical distance between locally impacted sites. For instance, the São Simão (PR1) and the Río de La Plata (RPL) showed similar eutrophication signs (especially high concentration of chlorophyll *a*) but their geographical distance is the largest one in this study. These "outliers" caused the reduction of the correlation observed value.

Regarding the vegetation influence, despite being considered as a major factor in the structure of aquatic habitats (Thomaz et al., 2008; Junk et al., 2014), no significant correlation with the water bodies' environmental characteristics or the geographical distance was observed, based on the Mantel test.

In the La Plata basin, both natural (e.g. floodplains) and manmade (e.g. reservoirs) barriers for solids and nutrient transportation, in addition to the land use in the catchments, are the most important structural determinants for the limnological characteristics. Intensive damming in the upper Paraná River sub-basin created a vast "lentic" mosaic macro-system, much different from the original lotic condition. Regional sources of suspended matter and nutrients were responsible for the "outlier" sites, what clearly demonstrate how eutrophication processes caused by human activities can disrupt natural patterns.

Acknowledgements

The authors thank Silvia Casanova and Jorge Portinho for help in field work expeditions; to FAPESP for the financial support (processes 2009/00014-6; 008/02015-7, 2009/00014-6, 2011/18358-3; 2009/11781-8; 2011/23444-6).

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Received: 04 August 2016
Accepted: 24 November 2016