The importance of a wetland for the water quality of a sewage-contaminated urban ecosystem

A importância de um alagado para a qualidade da água em um ecossistema urbano impactado por resíduos domésticos

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Abstract

Lakes and lagoons are abundant components of the natural landscape of the state of *Rio de Janeiro*, Brazil. However, due to human activities, many of those are under strong ecological impact. *Vigario* Lake and *Taquaruçu* Lake are important water bodies in the city of *Campos dos Goytacazes* but still receive domestic sewage along their margins. The water flows from *Vigario* to *Taquaruçu* Lake, passing through a wetland, which is fully colonized by aquatic macrophytes, especially *Typha domingensis* and *Eichhornia crassipes*. In this study, water samples were collected during a monthly monitoring of 12 months in 1999 and an intensive sampling in the dry and wet periods in 2000/2001 in representative stations along the study area for determination of physico-chemical and chemical variables. In the wetland, a place of anoxic characteristics, denitrification, ammonification and release of orthophosphate from the sediment to the water column could be detected, while other important limnological processes of oxidant waters could be observed in the lakes, despite the contamination. A controlled mesocosm experiment was designed to quantify the function of the wetland on the depuration of the waters from the *Vigario* Lake. Such artificial system could significantly remove biochemical oxygen demand in 84%, total and thermotolerant coliforms in 94% and 87% respectively, dissolved and total nutrients from the waters coming from the *Vigari*o Lake. For the removal of ammonium and dissolved phosphorus, the presence of aquatic macrophytes was mandatory in the system.

Key words: constructed wetlands; lakes; nitrogen; nutrients; phosphorus; wetlands.

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Resumo

Lagoas e lagunas são componentes importantes da paisagem natural no Estado do Rio de Janeiro. Contudo, devido a atividades antrópicas, muitos destes ambientes encontram-se impactados ecologicamente. A Lagoa do Vigário e a Lagoa Taquaruçu são corpos d'água importantes no município de Campos dos Goytacazes, mas ainda recebem esgoto doméstico das moradias situadas às suas margens. Neste sistema, a água flui da Lagoa do Vigário para a Lagoa Taquaruçu, passando por um alagado (brejo) inteiramente colonizado por macrófitas aquáticas, principalmente *Typha domingensis* e *Eichhornia crassipes*. Neste estudo foram coletadas amostras de água durante um monitoramento mensal por 12 meses em 1999 e durante dois períodos de coletas intensivas, uma no período seco e outra no período chuvoso em 2000/2001 em estações representativas ao longo da área de estudo. Nestas amostras foram determinadas variáveis químicas e físico-químicas. No alagado, um sistema de características anóxicas, foram detectados processos como desnitrificação, amonificação e liberação de orto-fosfato do sedimento para a coluna d'água. Outros processos limnológicos característicos de águas oxidantes foram detectados nas lagoas, apesar da contaminação. Um experimento controlado realizado em mesocosmos foi elaborado para quantificar a função do alagado na depuração das águas oriundas da Lagoa do Vigário. Este sistema artificial foi responsável por remover significativamente 84% da demanda bioquímica de oxigênio, 94% de coliformes e 87% de coliformes termotolerantes das águas da Lagoa do Vigário. Nutrientes dissolvidos e totais também foram removidos, embora em quantidades menores. Para a remoção de amônio e fósforo dissolvido, a presença de macrófitas aquáticas foi essencial ao sistema.

Palavras-chave: alagados construídos; fósforo; lagoas; nitrogênio; nutrientes; brejo.

Introduction

Natural aquatic ecosystems placed in urban zones are highly susceptible to fluctuations on their water chemistry. In ecological terms, the formation of urban communities of low income people in developing countries is followed by failures in the removal of domestic residues and their deposition in the closest water body (BRADLEY; and BARTRAM, 2013; VIANNA, 1991), causing the enrichment of organic matter and nutrients in the aquatic system.

Nitrogen (N) and phosphorus (P) are the most limiting nutrients in aquatic ecosystems (ELSER et al., 2007; HARPOLE et al., 2011), with co-limitation by these two nutrients being an important process in shallow lakes (MÜLLER; MITROVIC, 2015). Thus their simultaneous addition in water bodies stimulates photosynthesis, disrupting the equilibrium of the system, which starts to produce more organic matter than it is able to mineralize. This accumulation of biogenic material in the lake leads it to a process of "precocious oldness" (MITSCH; GOSSELINK, 2000), culminating in the acceleration of the transformation of an aquatic into a terrestrial ecosystem. Therefore, it is important to understand which processes are responsible for the maintenance of such environments as well as how the different components of the ecosystem contribute to its overall equilibrium.

Wetlands functions include the storage of nutrients in the microbiological and macrophytic biomasses, nutrient cycling, natural control of flooding and water treatment (JING et al., 2001). Wetlands act as important buffers to adjacent aquatic systems by assimilating nutrients and other contaminants from agricultural and urban runoff (BRIX, 1994). Due to the continuous biomass accumulation, aquatic macrophytes have been studied and referenced by many authors as very efficient plants on nutrients and organic matter removal in those environments (BRIX, 1994; GUMBRICHT, 1993; HILL et al., 1997; PETRUCIO; ESTEVES, 2000; OZIMEK et al., 1990; WEISNER et al., 1993).

The group of macrophytes encompasses a wide range of plants, which can vary from macroalgae to angiosperms, such as genera *Chara* and *Typha*, respectively (MARGALEF, 1983).

In constructed wetlands, pollutants are removed from the water through the interaction of physical, chemical and biological processes, in which sedimentation, precipitation, adsorption, assimilation by the plants and microbiological activity are the most important forms of nutrient and pollutants removal. The use of constructed wetlands for the improvement of the water quality is being largely studied, mainly in developing countries (AYAZ; AKÇA, 2001) and has increased worldwide in recent decades to reduce nutrient concentrations and to degrade organic compounds (MCINERNEY; HELTON, 2016). The main advantages of the utilization of such systems are: (i) the occurrence of the physical, chemical and biological processes of water treatment at the same time; (ii) the low implementation and operation costs in relation to the traditional methods (AYAZ; AKÇA, 2001); (iii) the establishment of an aesthetically pleasant sewage treatment station (AYAZ; AKÇA, 2001); (iv) the use of a method that is environmentally acceptable for sewage treatment, since it is based on natural processes (DECAMP; WARREN, 2000).

These systems can be used in different areas and with different purposes. They have been used in the treatment of domestic residues of small communities of urban and agricultural areas. Other possible applications are the treatment of industrial effluents (MCINERNEY; HELTON, 2016) and animal wastes. Constructed wetlands are able to remove more than 90% of the organic budget of total nitrogen and phosphorus, under certain conditions, and can provide an economy of 70% in material and of 80% in energy, when compared to the traditional systems of water treatment (LUEDERITZ et al., 2001). Gschlöbl et al. (1998) could detect a removal of 50% in the concentrations of dissolved chlorophyll a and of 60% of the suspended material in the water, after passing through a subsurface flux constructed wetland. Jing et al. (2001) detected a removal of 80% of ammonium, 85% of orthophosphate and a maximum removal of 51% of the chemical oxygen demand, while Huddleston et al. (2000) verified a removal of 80% in the biochemical oxygen demand testing the efficiency of a constructed wetland in the treatment of an effluent of a petroleum refinery. As in natural wetlands, aquatic macrophytes have many physical, chemical and biological properties related to the treatment of the water in constructed wetlands, which make them indispensable in these ecosystems (BRIX, 1994).

The natural water bodies in *Campos dos Goytacazes*, Brazil, have been used for economic and recreational purposes, but now most of them are under a strong human impact process. This research was carried out in an unstudied wetland system. It is formed by *Vigario* Lake (0.3 km^2), which is connected to a wetland (0.4 km^2) and this is connected to *Taquaruçu* Lake (0.3 km^2), located in a low-income urban zone of the city (Figure 1). The water flows from the *Vigario* Lake towards *Taquaruçu* Lake, passing through the wetland, which is fully colonized by macrophytes. Along the system, especially in the *Vigario* Lake, domestic residues such as sewage and garbage are disposed with no previous treatment (personal observations; PRECIOSO et al., 2010). The purpose of this paper is to study the limnological characteristics of the two lakes and their linking wetland in face of the sewage contamination. For this, the following specific targets were outlined:

(1) To study limnological differences amongst the components of the system to investigate whether the natural wetland acts depurating the waters coming from the *Vigario* Lake, through a monthly monitoring program besides an intensive sampling during the dry and wet seasons,

(2) To quantify the role of the wetland on the removal of nutrients through a controlled mesocosm experiment.

Material and Methods

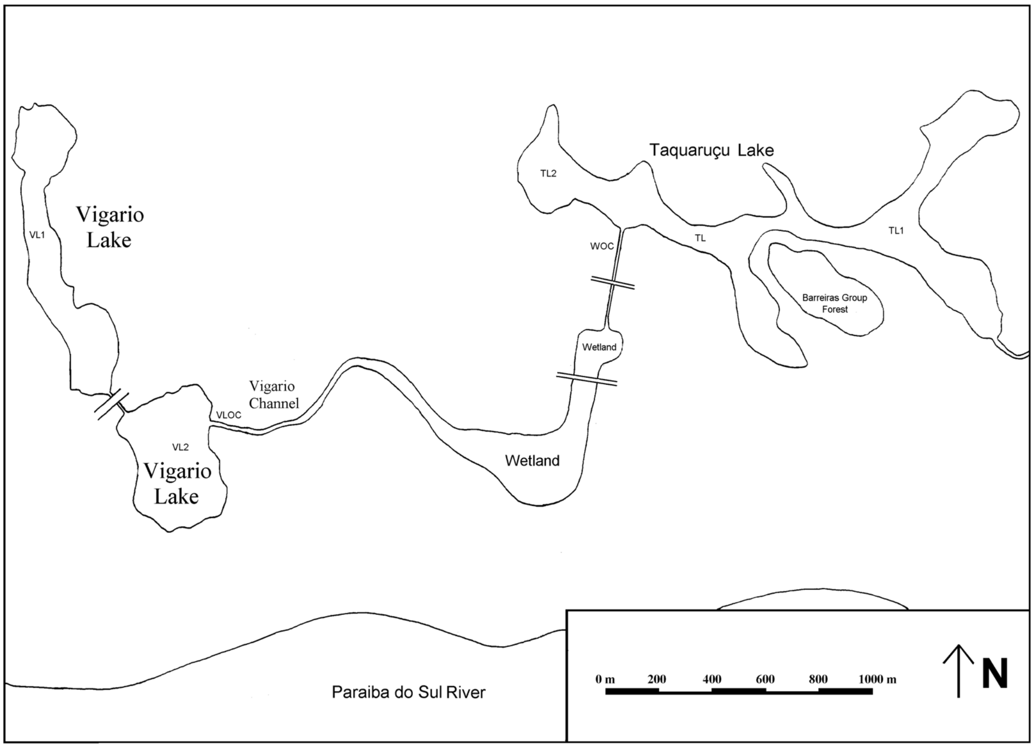
Field study

The studied system (21º45'S, 41º19'W) is situated in the urban area of Campos dos Goytacazes, a city of almost half a million inhabitants located in northern region of Rio de Janeiro State, Brazil. This region has a peripheral development in relation to the Brazilian economy, pointed out as one of the poorest regions in Brazil, both socially and economically (VIEIRA, 1998).

Vigario Lake is connected to *Taquaruçu* Lake through a wetland (Figure 1), forming the hereafter mentioned as the '*Vigario-Taquaruçu* system'. *Vigario* Lake (0.3 km^2) is a shallow water body (mean depth of about 1.2 m during the wet season) and having an intense human colonization on its margins, with sewage and garbage being deliberately disposed in the lake. The wetland (0.4 km^2) is fully colonized by aquatic macrophytes and its margins are also used as a garbage and sewage disposal area. *Taquaruçu* Lake (0.3 km^2) is also a shallow system (mean depth of about 2.0 m during the wet season) but is under a lower human influence, presenting a little fragment of a Barreiras Group forest (VILLAS BÔAS et al., 2001) on its margins, besides a cattle grazing area. The predominant macrophytes in the area are *Typha domingensis* and *Eichhornia crassipes*; these plants form dense clusters, moving according to the direction of the wind.

Surface water samples were collected monthly along 12 months in the year of 1999 in three representative stations along the study area (Figure 1), including the *Vigario* Lake outflow channel (VLOC) that feeds the wetland, the Wetland outflow channel (WOC) that feeds *Taquaruçu* Lake, and a station in the middle of *Taquaruçu* Lake (TL). In order to better characterize the system and to expand the spatial sampling, surface and bottom water samples were collected in five consecutive weeks in the dry season (Jul-Aug-2000) and during four consecutive weeks in the wet season (Jan-Feb-2001). In these field surveys, the same three stations cited above were maintained and other four were added, two in the *Taquaruçu* Lake (TL1 and TL2) and the other two in the *Vigario* Lake (VL1 and VL2) (Figure 1). During the studied periods, rainfall and incident radiation data were obtained at the Meteorological Station from the Universidade Estadual do Norte Fluminense, located next to the system.

Figure 1 – Illustrative drawing of the *Vigario-Taquaruçu* System. The water flows from *Vigario* to *Taquaruçu* Lake, passing through the wetland



Note: The sampling sites are shown. VL1 and VL2 are located at the middle of the Vigario Lake segments, sampled in the dry and wet periods. VLOC is the sampling station at the flow channel of *Vigario* Lake, representing both the outflow of the *Vigario* Lake and the inflow of the wetland. WOC is the channel that represents both the outflow of the wetland and the inflow of the *Taquaruçu* Lake. TL1 and TL2 are the stations in *Taquaruçu* Lake sampled only in the dry wet and periods sampling; TL was also sampled in this period, additionally to the monthly monitoring.

Analytical Procedures

Water transparence and depth were measured with a Secchi disk tied to a rope and thrown from the boat into the water. Measurements of pH, water temperature, electric conductivity, EH and dissolved oxygen were taken in situ with portable meters. The last parameter was taken only when positive values of EH were detected. A van Dorn sampler was used to acquire bottom water samples, and these were immediately transferred to a 1 L plastic bottle. The surface water was sampled with plastic bottles put directly into the water column. Such samples were kept in a refrigerated box, and then taken immediately to the laboratory.

In the laboratory, subsamples of 50 mL were used to determine total alkalinity by potentiometric titration (GRAN, 1952). Other subsamples were filtered through Whatman GF/F filters. The filters were stored and frozen for further determinations of chlorophyll a (NUSCH; PALME, 1975). A subsample of this filtrate was preserved with HCl 4 N for later determination of dissolved iron through the colorimetric ferrozin method (CARMOUZE, 1994). The remnant filtrates were kept in plastic bottles and frozen for later colorimetric determination of ammonium (indophenol method), nitrite (sulfanilamide hydroclorate method), and orthophosphate (ascorbic acid method) according to Carmouze (1994). Nitrate was determined by colorimetry with a flow injection analysis system (FIA, Asia-Ismatec). Total inorganic nitrogen (TIN) is obtained by the sum of the ammonium, nitrite and nitrate concentrations.

Total dissolved nitrogen (TDN) was determined using colorimetry with a flow injection analysis system (FIA, Asia-Ismatec) after a digestion with alkaline potassium persulphate solution. Total dissolved phosphorus (TDP) was assessed using the colorimetric ascorbic acid method after digestion with acid potassium persulphate; non-filtered subsamples were used to determine total nitrogen (TN) and total phosphorus (TP) using the same method. Dissolved organic nitrogen (DON) and dissolved organic phosphorus (DOP) were obtained by subtracting TDN from TIN, and TDP from orthophosphate respectively.

The dissolved cations Na^+, Ca^{2+}, K^+, Mg^{2+} were measured by atomic emission spectrometry with induced plasma (ICP-AES, Varian). The anions SO_4^{-2} e Cl^- were determined by a high performance liquid cromatographer (HPLC, Merck-Hitachi L-6200) with a conductivity detector.

Statistical Treatment of the Data

To test for differences between the sampling stations in the monthly monitoring program, Mann-Whitney U Test was chosen, using the software Statistisca 6.0. Such nonpapametrics test was applied to the data since they don't have a normal distribution, verified using the same software as cited above. This statistics was applied to test the differences for each pair of stations (VLOC versus WOC, WOC versus TL and VLOC versus TL) with a confidence interval of 95% ($p \leq 0.05$). The same procedure was performed to test for differences between surface and bottom water samples taken during the wet and dry periods intensive monitoring.

Mesocosm experiment

In August 2002 six constructed wetlands were built in asbestos boxes of 40 dm^3 each. In each box an inflow and an outflow system were installed, using plastic pipes and taps in a way that both inflow and outflow taps were disposed under the sediment. In each of the six boxes we put approximately 30 dm^3 of the clayey substrate taken from the natural wetland located in the *Vigario-Taquaruçu* system and homogeneous young individuals of *Typha domingensis* were planted in three of them. This macrophyte is highly abundant in the natural wetland mentioned in the sections above, developing in monoespecifics stands and reproducing through seeds and persistent rhizomes, being adapted to disturbed and euthrophic habitats (LORENZEN et al., 2001). The common names for the plants of the genera *Typha* are "taboa" in Brazil, "cattail" in North America, "reedmace" in the United Kingdom, "cumbugi" in Australia and "bulrush" in New Zealand. It is important to note that these plants were collected in the natural wetland from the *Vigario-Taquaruçu* system, and the amount of individuals planted in each of the three boxes was equivalent to their dominance in the field, which were measured previously to the experiment with three quadrats of 0.25m^2. A 250 liters box was placed 70 cm above the six constructed wetlands and fed daily with water from the *Vigario* Lake. This water was thus distributed to the artificial wetlands at a rate of 2 liters per day through connected pipes.

During three months a continuous subsurface flux was established by constant dripping of the outflow tap. At each five days samples were taken for immediate determination of temperature, electric conductivity, pH, EH and dissolved oxygen using field equipment previously calibrated in the lab. A second subsamble was taken to the lab for determination of total alkalinity. A third subsample was filtered through glassfiber filters GF/F Whatman with average porosity of 0.7 µm for further determinations of dissolved nutrients. A fourth subsample was taken and frozen for further determination of total nutrients.

A volume of 100 mL of the filtered subsample was stored in amber flasks previously washed with sulphocromic solution containing 5 mL of phosphoric acid 10% and stored in the fridge for further determination of dissolved organic carbon after acidification with cloridric acid 2 N through catalytic oxidation using the equipment TOC 5000 Shimadzu.

Orthophosphate, total dissolved phosphorus, dissolved organic phosphorus total phosphorus, ammonium, nitrite, nitrate, dissolved inorganic nitrogen, dissolved organic nitrogen and total nitrogen were determined using the same methods as described above for the field study.

Total and thermotolerant coliforms were determined through the multiple tube fermentation method (APHA, 1992). Biochemical oxygen demand was measured after incubation on the dark for 5 days and oxygen determined by the Winkler method (CARMOUZE, 1994; BARTRAM; BALANCE, 1996);

Statistical Treatment of the Data

We used one-way ANOVA followed by Tukey's test to check for differences in the chemical variables determined in the inflow waters, in the outflow waters of vegetated constructed wetlands (CWs) and in the outflow waters of the unvegetated CWs. The assumption of normality was checked for all datasets using Kolmogorov-Smirnov test. Data were log- or square root-transformed when necessary to allow the above-mentioned parametric analyses. All analyses were done with Statistica 6.0.

Results

Field study

Average rainfall and incident radiation were 0.2 mm and 169 $W.m^{-2}$ per day respectively in the dry period (Winter), whereas these values increased to 0.8 mm and 316 $W.m^{-2}$ per day in the wet period (Summer). Water temperature was systematically higher during the wet period. The average depths in the stations in the middle of *Vigario* Lake were 1.2 and 0.9 m in the wet and dry periods respectively, and the transparence was 0.3 m in both stations. For the Taquaruçu Lake, the depths were 2.0 and 1.1 and the transparencies were 0.6 and 0.5 in the wet and dry periods respectively.

The lowest pH values were detected at the Wetland Outflow Channel (WOC), whereas the *Vigario* Lake Outflow Channel (VLOC) often had the highest ones, especially during the wet period (Table 1; Figure 2a; Figure 3a). Oppositely, higher pH values were measured in the Taquaruçu Lake during the dry period. VLOC and WOC didn't differ in relation to total alkalinity (Table 1), while Taquaruçu Lake (TL) presented the lowest values (Table 1; Figure 2b).

Negative EH values persisted in WOC from January to December 1999, and a positive peak was detected in January 2000 (Figure 2c), when waters from Paraiba do Sul River entered the *Vigario-Taquaruçu* system, inverting the usual direction of the water flow. Considering this, dissolved oxygen could only be measured at this station in this month, achieving a value of 4.3 $mg.L^{-1}$; the other two stations presented positive EH values and values of dissolved oxygen were always over 1.7 $mg.L^{-1}$ (Figure 2d). Both EH and dissolved oxygen tended to present the highest values during the dry period at the sampled stations, except in WOC, where negative EH values were always measured (Figures 3b and 3c respectively).

Electrical conductivity was continuously higher in WOC in relation to the other stations, though not significantly (Figure 2e; Table 1). The minimal values in VLOC and WOC (0.13 and 0.04 $mS.cm^{-1}$, respectively) were measured in March, after a strong rain, pointed out in Figure 2g. The incident solar radiation in the sampled periods showed a seasonal variation, as can be seen in Figure 2h. Also in the dry period, electric conductivity and total alkalinity were higher than in the wet period (Figure 3d and 3e). The wetland, represented by WOC, showed the highest values for total alkalinity both in the dry and wet seasons (Figure 3e).

Chlorophyll a was highest in VLOC along almost all the studied months. The only exception was also March, when it dropped from an average concentration of 121 $\mu g.L^{-1}$ to 3 $\mu g.L^{-1}$. The WOC had the lowest chlorophyll a values, while Taquaruçu Lake showed intermediate concentrations between VLOC and WOC (Figure 2f), being the three stations significantly different from one another (Table 1). The highest values for chlorophyll a were observed in TL in the dry period in comparison to the wet one. Oppositely, the highest concentrations were detected in the wet period in WOC and VLOC, when WOC presented higher concentrations than Taquaruçu Lake (Figure 3f).

Nitrite and nitrate were significantly different in VLOC and WOC (Figures 4a and 4b; Table 1). Ammonium concentrations were very unstable, and although the values were not statistically different ($P = 0.66$), the WOC tended to present the highest values

Table 1 – List of the parameters Z and p calculated through Mann-Whitney U Test for each pair of stations. The variables analyzed were pH, total alkalinity, EH, dissolved oxygen, electric conductivity, chlorophyll a, ammonium, nitrite, nitrate, total nitrogen, orthophosphate, total dissolved iron, total dissolved phosphorus and total phosphorus.

Pair of Stations	U Test Parameter	pH	Total Alc.	EH	DO	Electr. Cond.	Chl-a	NH_4	NO_2	NO_3	TN
WOC x VLOC	*z*	4.04	-1.61	-3.46	-	0.20	-4.04	-0.43	2.88	3.92	1.88
	p	0.00005	0.10597	0.00053	-	0.83980	0.00053	0.66500	0.00389	0.00087	0.02824
WOC x LT	*z*	-3.75	3.34	-3.52	-	1.12	-3.35	3.49	-2.04	-3.57	3.75
	p	0.00017	0.00081	0.00043	-	0.26020	0.00081	0.00047	0.04041	0.00034	0.00017
VLOC x LT	*z*	2.16	2.77	3.46	0.23	1.12	3.52	2.97	1.61	2.37	3.34
	p	0.30390	0.05587	0.00053	0.81736	0.26024	0.00043	0.00294	0.10590	0.01793	0.00081

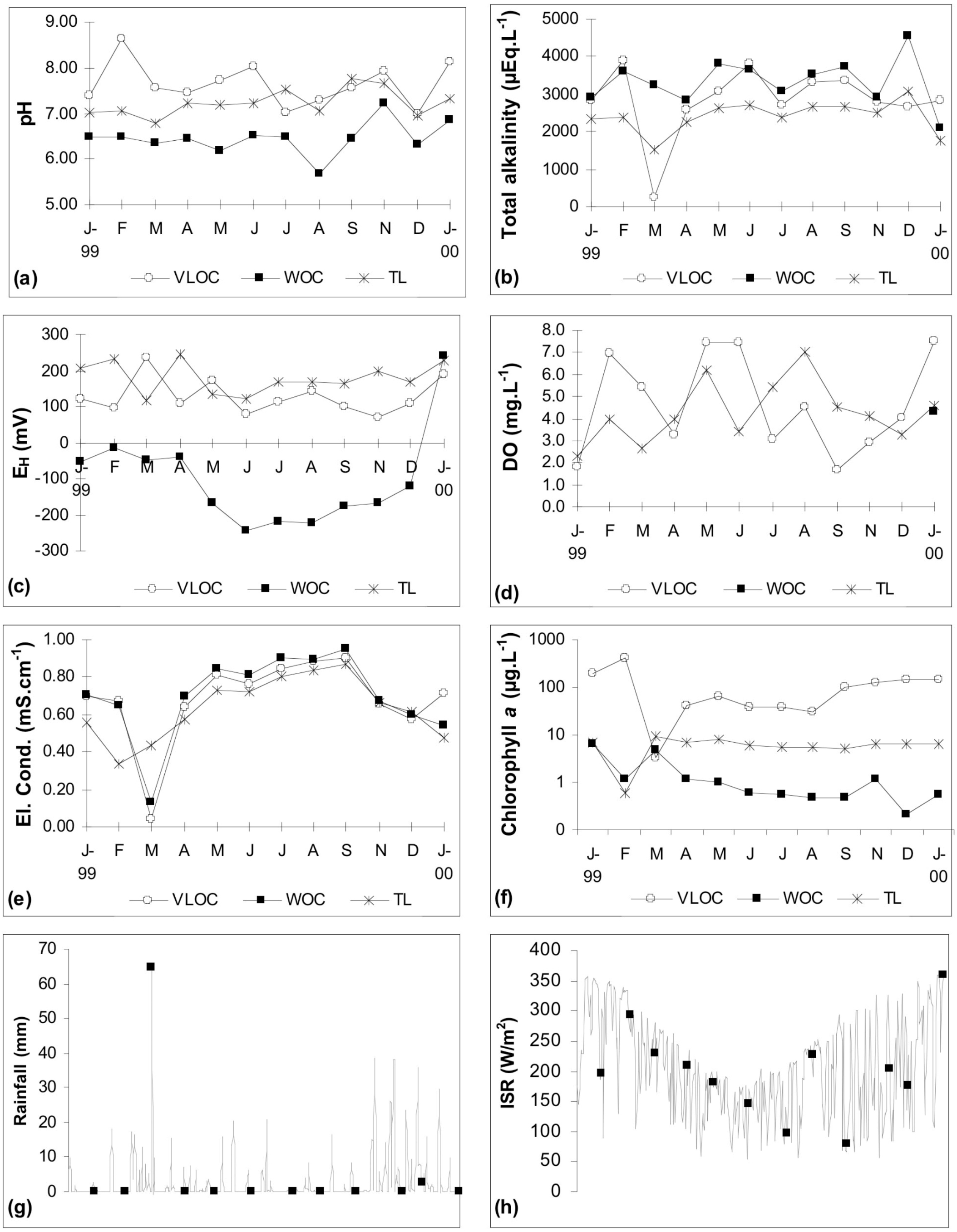
Continua »»»

»»» Conclusão.

Pair of Stations	U Test Parameter	PO_4	TDF_e	TDP	TP
WOC x VLOC	*z*	-2.19	-4.04	-1.55	-0.17
	p	0.02824	0.00005	0.11904	0.86240
WOC x LT	*z*	3.17	-3.117	3.40	-3.46
	p	0.00149	0.00182	0.00065	0.00053
VLOC x LT	*z*	0.66	-3.406	2.57	3.46
	p	0.50672	0.00065	0.01019	0.00053

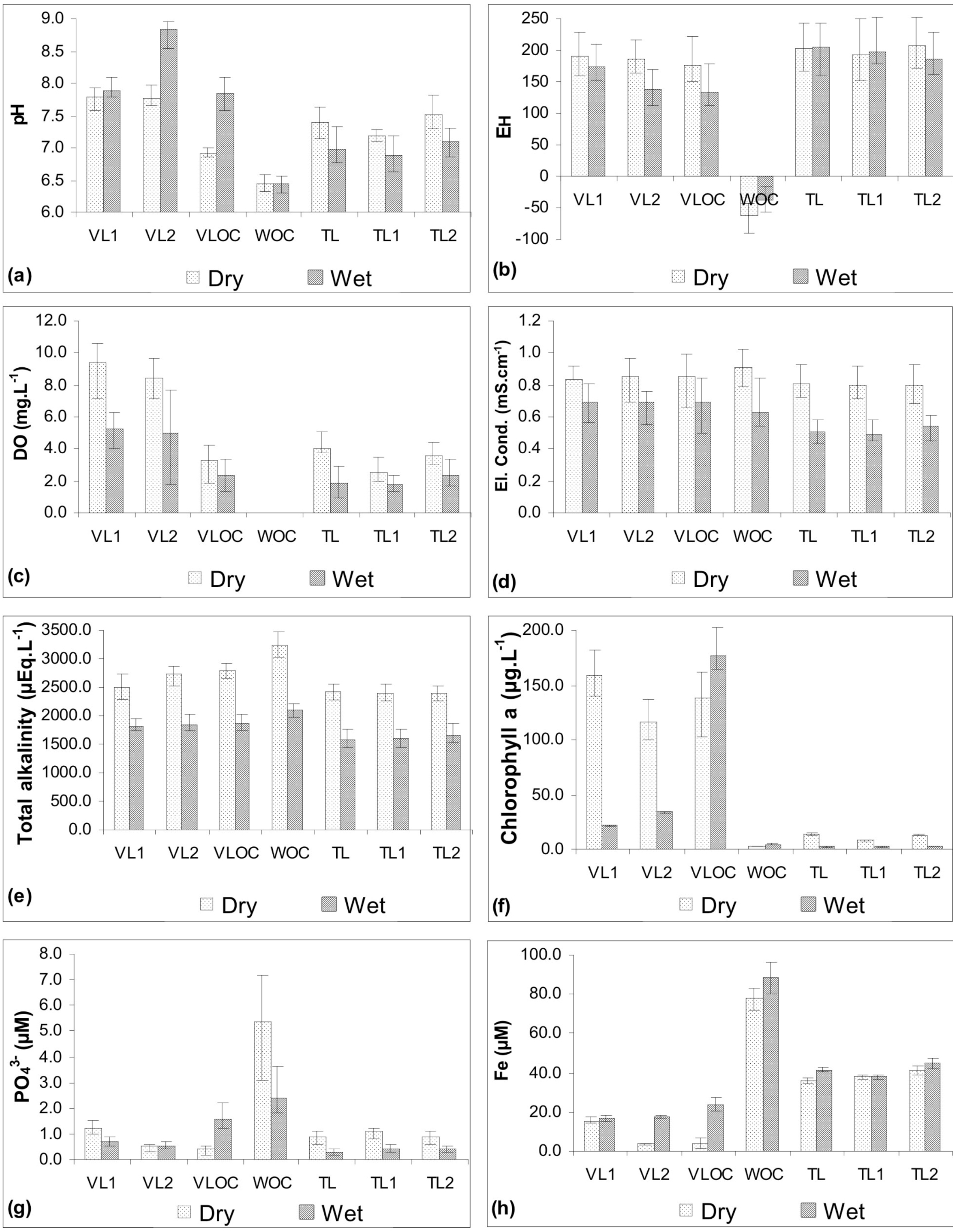
Consider $p \leq 0.05$ and n = 12.

Figure 2 – Water pH, total alkalinity, EH, dissolved oxygen, electric conductivity and chlorophyll values for the monthly monitoring (Jan 1999 to Jan 2000) at the *Vigario* Lake outflow channel (VLOC), Wetland outflow channel (WOC) and *Taquaruçu* Lake (TL)



Note: Rainfall and incident solar radiation for the sampling periods are shown, and the black squares indicate the sampling days (data from the UENF meteorological station).

Figure 3 – Average values of pH, EH, dissolved oxygen, electric conductivity, total alkalinity, chlorophyll a, orthophosphate and total dissolved iron obtained during the dry and wet periods intensive monitoring campaigns in 2000-2001 in seven stations along the system (see Figure 1)



Note: Dry period, n=10; wet period, n=8. NM – Not measured.

when compared to the inflow (VLOC) (Figure 4c). Ammonium and nitrite had their higher concentrations during the dry period in all sampled stations (Figures 5a and 5b). It's important to outline that ammonium concentrations were strongly increased in the wetland during the dry period while nitrite had assumed the lowest concentrations. Higher concentrations of nitrate (Figure 5c) were measured in all stations during the wet period; the wetland, represented by WOC, had the lowest concentrations. Since the concentrations of ammonium were much higher than the other inorganic forms of nitrogen, dissolved inorganic nitrogen (DIN) and ammonium showed the same pattern (Figure 5d).

Orthophosphate and total dissolved iron concentrations were generally highest in WOC than in the other stations (Figure 4e and 4f), especially in the dry period (Figure 3g and 3h). Total dissolved phosphorus followed a similar pattern to orthophosphate (Figure 4g).

The Taquaruçu Lake had significantly the lowest values of total nitrogen and phosphorus in relation to the other sampling stations (Table 1; Figures 4d and 4h). Total phosphorus (TP) was highest in VLOC during the rainy months (Jan, Feb, Mar, Dec 1999, and Jan 2000) in comparison to the other the sampled stations, except in WOC, where negative EH values were always measured (Figures 3b and 3c respectively).

Electrical conductivity was continuously higher in WOC in relation to the other stations, though not significantly (Figure 2e; Table 1). The minimal values in VLOC and WOC (0.13 and 0.04 $mS.cm^{-1}$, respectively) were measured in March, after a strong rain, pointed out in Figure 2g. The incident solar radiation in the sampled periods showed a seasonal variation, as can be seen in Figure 2h. Also in the dry period, electric conductivity and total alkalinity were higher than in the wet period (Figure 3d and 3e). The wetland, represented by WOC, showed the highest values for total alkalinity both in the dry and wet seasons (Figure 3e).

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Nitrite and nitrate were significantly different in VLOC and WOC (Figures 4a and 4b; Table 1). Ammonium concentrations were very unstable, and although the values were not statistically different (P = 0.66), the WOC tended to present the highest values when compared to the inflow (VLOC) (Figure 4c). Ammonium and nitrite had their higher concentrations during the dry period in all sampled stations (Figures 5a and 5b). It's important to outline that ammonium concentrations were strongly increased in the wetland during the dry period while nitrite had assumed the lowest concentrations. Higher concentrations of nitrate (Figure 5c) were measured in all stations during the wet period; the wetland, represented by WOC, had the lowest concentrations. Since the concentrations of ammonium were much higher than the other inorganic forms of nitrogen, dissolved inorganic nitrogen (DIN)

Figure 4 – Nitrite, nitrate, ammonium, total nitrogen, orthophosphate, dissolved total iron, total dissolved phosphorus and total phosphorus values for the monthly monitoring (Jan 1999 to Jan 2000) at the *Vigario* Lake outflow channel (VLOC), Wetland outflow channel (WOC) and *Taquaruçu* Lake (TL)

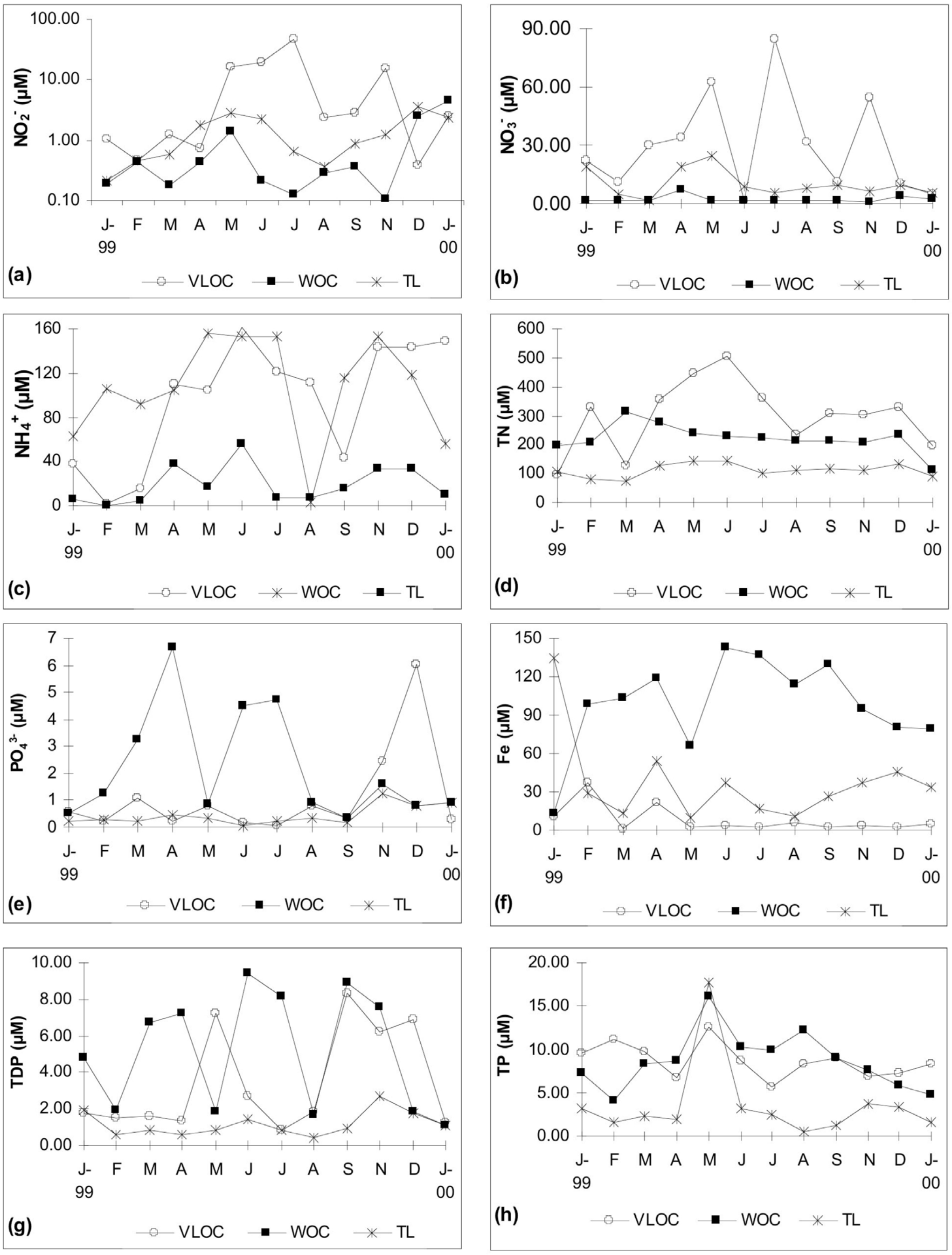
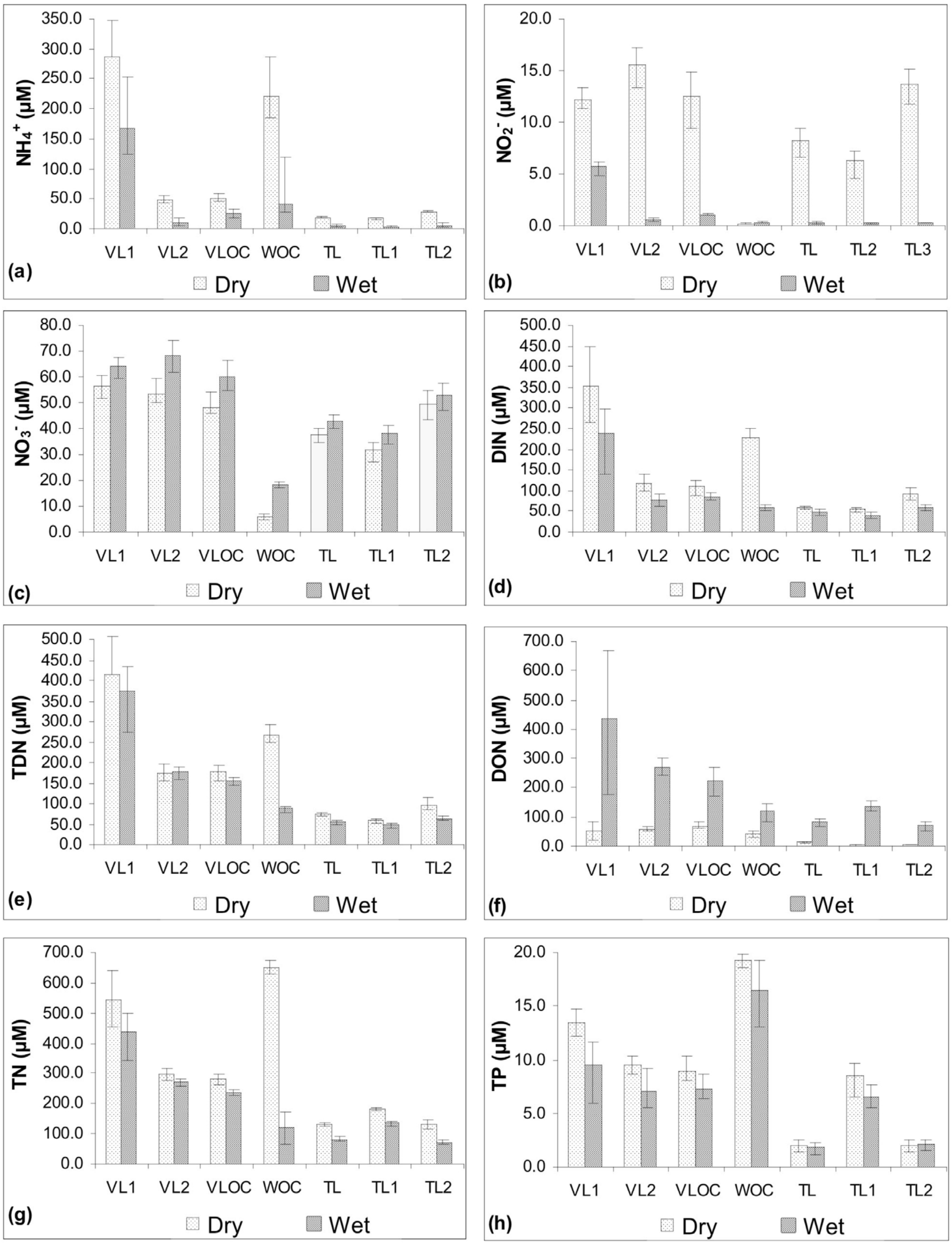


Figure 5 - Average values of ammonium , nitrite, nitrate, dissolved inorganic nitrogen, total dissolved nitrogen, total organic nitrogen, total nitrogen and total phosphorus obtained during the dry and wet periods intensive monitoring campaigns in 2000-2001 in seven stations along the system (see Figure 1)



Note: Dry period, n=10; wet period, n=8. NM – Not measured.

Table 2 – Averages and standard deviations of the concentrations of the major dissolved cations and anions determined in two surface and bottom water samples in the dry period and in the wet period.
NM = Not measured.

	Cl^- (µM)		SO_4^{2-} (µM)		Na^+ (ppm)		K^+ (ppm)		Ca^{2+} (ppm)		Mg^{2+} (ppm)	
Stations	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet
VL1 SUR	3207 (110)	2936 (54)	73 (14)	64 (2)	50 (10)	46 (6)	17 (3)	12 (2)	11 (2)	12 (6)	9 (2)	6 (1)
VL1 BOT	3104 (104)	2441 (525)	108 (36)	94 (36)	48 (12)	47 (17)	16 (2)	14 (0)	10 (3)	13 (6)	10 (1)	7 (0)
VL2 SUR	4505 (151)	3632 (501)	146 (14)	91 (28)	35 (0)	53 (0)	27 (17)	14 (3)	9 (2)	19 (5)	6 (3)	7 (2)
VL2 BOT	NM	3521 (527)	NM	132 (3)	NM	69 (18)	NM	22 (6)	NM	20 (3)	NM	7 (2)
VLOC	4942 (44)	3238 (84)	102 (1)	101 (3)	42 (1)	42 (9)	14 (8)	34 (36)	7 (2)	20 (14)	4 (1)	5 (1)
WOC SUR	10786 (227)	9489 (190)	77 (2)	63 (2)	31 (4)	58(10)	13 (10)	15 (20)	9 (0)	9 (12)	7 (4)	3 (4)
WOC BOT	9955 (119)	9441 (269)	82 (3)	59 (4)	29 (0)	71 (8)	19 (0)	16 (2)	9 (0)	16 (3)	9 (0)	9 (0)
TL SUR	6181 (166)	4978 (214)	166 (1)	144 (22)	51 (25)	37 (14)	15 (5)	8 (4)	12 (3)	14 (3)	8 (2)	6 (3)
TL BOT	6433 (172)	4730 (140)	173 (6)	130 (25)	36 (1)	56 (6)	10 (4)	11 (2)	11 (3)	14 (0)	6 (2)	7 (1)
TL1 SUR	7755 (80)	6575 (74)	156 (4)	122 (4)	31 (2)	48 (6)	12 (8)	10 (1)	10 (4)	14 (1)	7 (5)	7 (1)
TL1 BOT	5965 (169)	6143 (253)	169 (3)	124 (9)	48 (7)	43 (5)	17 (6)	12 (3)	12 (0)	15 (1)	6 (2)	9 (2)
TL2 SUR	5789 (222)	4393 (130)	138 (23)	130 (5)	38 (3)	44 (16)	23 (16)	10 (6)	12 (3)	12 (2)	5 (3)	7 (4)
TL2 BOT	6184 (77)	4095 (141)	141 (22)	141 (19)	46 (12)	42 (8)	23 (18)	8 (3)	14 (1)	12 (1)	5 (2)	6 (2)

and ammonium showed the same pattern (Figure 5d).

Orthophosphate and total dissolved iron concentrations were generally highest in WOC than in the other stations (Figure 4e and 4f), especially in the dry period (Figure 3g and 3h). Total dissolved phosphorus followed a similar pattern to orthophosphate (Figure 4g).

The *Taquaruçu* Lake had significantly the lowest values of total nitrogen and phosphorus in relation to the other sampling stations (Table 1; Figures 4d and 4h). Total phosphorus (TP) was highest in VLOC during the rainy months (Jan, Feb, Mar, Dec 1999, and Jan 2000) in comparison to the other sampling stations (Figure 4h); during the dry season, TN and TP were highest in WOC (Figures 5g and 5h).

The highest concentrations of the measured anions were detected in the dry period in all studied stations (Table 2). The highest values of chloride and the lowest values of sulphate were detected in WOC. The cations (Na^+, Ca^{2+}, K^+ and Mg^{2+}) had similar distributions along the studied system. The Cl- to SO_4^{2-} ratio didn't show any important variation for the stations referring to the lakes, as well as for VLOC. It can be observed, however, an important increase in this ratio in WOC in in relation to the other stations (Appendix 1).

Mesocosm experiment

The constructed wetlands were effective to quantify the role of the wetland on the depuration of the waters coming from the *Vigario* Lake. Our constructed wetlands were responsible for significant changes in all studied variables in relation to the inflow waters (Table 3).

Biochemical oxygen demand, total and thermotolerant coliforms, nitrite, nitrate, total nitrogen, total dissolved phosphorus and total phosphorus were equally removed from inflow waters in the vegetated and unvegetated CWs, whereas concentrations of ammonium, inorganic dissolved nitrogen and orthophosphate were incremented in the unvegetated constructed wetlands in relation to the inflow waters (Table 5; Appendix 2). Total dissolved nitrogen was the only variable removed at significantly higher rates in the vegetated wetlands in relation to the unvegetated ones.

Table 3 – Percentages of removal of the studied variables in the vegetated and unvegetated constructed wetlands in relation to the inflow waters (water from the *Vigario* Lake)

Variable	Vegetated	Unvegetated
Biochemical oxygen demand	84*	81*
Total coliforms	87*	82*
Thermotolerant coliforms	94*	91*
Ammonium	81*†	+65*
Nitrite	50*	50*
Nitrate	82*	73*
Inorganic dissolved nitrogen	83*†	42* (increment)
Total dissolved nitrogen	63*†	51*
Total nitrogen	58*	39*
Orthophosphate	75*†	50* (increment)
Total dissolved phosphorus	74*	48*
Total phosphorus	67*	67*

Note: Data were tested by ANOVA followed by Tukey's test (n=3, $p<0.05$). * significantly different from the inflow waters; † significantly higher than the unvegetated constructed wetlands. "Increment" means an increase in relation to the concentrations in the inflow waters.

Discussion

Field survey

Waters flow faster at the *Vigario* Lake outflow channel (VLOC) and at the wetland outflow channel (WOC), when compared to the *Taquaruçu* Lake (TL). In the field survey of March 1999, performed under a strong rain, the electric conductivity showed different patterns in these lotic and lentic compartments. This variable was strongly decreased in WOC and VLOC, due to the higher dilution of the waters in this lotic compartment (MENEZES et al., 2013), whereas in TL this variable was not modified.

The quantitative analysis of chlorophyll a showed higher values in VLOC, i.e., in the inflow waters, when compared to WOC. It indicates a high phytoplanktonic productivity in the lake. Since macrophytes are the main responsibles for the primary productivity in wetlands (DELPHINE et al. 2015), WOC had a low chlorophyll a content but a high abundance of macrophytes, in a community composed especially by *Typha domingensis* Pers., *Salvinia auriculata* Aubl. and *Eichhornia crassipes* Mart.

The wetland, represented by the Wetland Outflow Channel, had lower medium EH and pH values than its inflow waters, the VLOC station. Total alkalinity was statistically the same in VLOC and WOC. These suggest the occurrence of anaerobic decomposition activity in the wetland and of a high primary productivity in the inflow waters. As mentioned in the previous paragraph, the primary productivity in the wetland is also elevated, but it is mainly accomplished by the aquatic macrophytes. Nevertheless, the process of mineralization of the organic matter tends to be outlined on this part of the system, when compared to the other sampling stations. Such approach can be corroborated by the electric conductivity, which was temporally higher in WOC, and by the dissolved oxygen, which had varied from 1.70 to 7.48 mg.L^{-1} in VLOC. In WOC, due to its reductant characteristics, dissolved oxygen could only be detected in January 2000, when an elevation in the level of Paraíba do Sul River occurred due to a strong rain and injected its more oxygenated waters in the *Vigario-Taquaruçu* system. These remarkably well-defined environmental trophic characteristics are corroborated by the EH, dissolved oxygen and electric conductivity data from the intensive monitoring campaign during the dry period (Figures 3b, 3c and 3d).

As demonstrated for other natural wetland systems (e.g. MITSCH et al., 2005; ZEDLER, 2003), nitrite and nitrate coming from the *Vigario* Lake were retained by the wetland. Also in the wetland, high levels of ammonium and low levels of nitrate can indicate the respective occurrence of ammonification and denitrification (BURGIN; HAMILTON, 2007; VYMAZAL et al., 2007). The high chloride to sulphate ratios in the wetland in relation to the other stations also show the possibility of occurrence of sulphate reduction as a way of decomposition of the organic matter. The observed high total alkalinity values in the wetland corroborate the possibility of occurrence of such anaerobic processes of decomposition of the organic matter in this wetland.

Oxidant conditions associated to low concentrations of total dissolved iron can indicate the formation of ferric phosphate (PONNAMPERUMA, 1972), which can be occurring in VLOC. On the other hand, the inverse chemical process is observed in the wetland (releasing of ferric phosphate from the sediment to the water column), beyond ferri-reduction, another anaerobic process of organic matter degradation. It is important to note, however, that domestic residues are discharged along the entire system, which can contribute to the higher concentrations of orthophosphate in the wetland.

The station TL1 (at the most distal portion of the Taquaruçu Lake) is intensely colonized by macrophytes of the genus *Ceratophyllum*. The higher levels of total nitrogen and phosphorus in TL1 when compared to the other stations in Taquaruçu Lake can be associated to the senescence of these plants in this part of the lake. The high concentrations of the organic phases of nitrogen and phosphorus in VL1 (the most distal portion of the *Vigario* Lake) can accelerate the process of oldness of such part of the system; the dry period seems critical, accumulating more material in early stages of decomposition, as shown for total nitrogen and total phosphorus.

Total phosphorus had similar concentrations in VLOC along the studied year, ranging from 5.6 to 12.5 μM in the monthly monitoring. These concentrations are amongst the highest ones reported to other lakes and lagoons from the region (Table 4). In WOC, the increase of total phosphorus concentrations in the dry months can indicate that this period is also critical for the wetland due to the accumulation of the primary products of decomposition of the aquatic macrophytes. The presence of these plants also works as a positive aspect concerning to the improvement of the water quality in the wetland. However, due to the lack of management and harvesting of such macrophytes, they accumulate along the wetland and work as another source of organic matter, concurring with the alloctonous material coming from *Vigario* Lake added via sewage disposal. The tendency of disappearance of shallow lakes through its conversion to wetlands is irreversible, though very slow (BJÖRK, 2010). With this human interference, the process can be very accelerated.

Although *Vigario-Taquaruçu* System is inserted in the urban area and it is under strong human impact, well-defined tendencies could be observed in relation to the main processes that characterize wetlands and lakes. This study clearly shows that the wetland plays an important role on the retention and/or the exportation of nitrogen and phosphorus (and even iron) in the system. However, due to the contamination along its margins, it was impossible to quantify such processes in the field and this was the reason why a mesocosm experiment was setup, with results shown below.

Table 4 – Comparative table of total nitrogen and total phosphorus concentrations, including some other lakes and lagoons additionally to the stations at the *Vigario* Lake

Study Site (Reference)	Total Nitrogen (µM)	Total Phosphorus (µM)
Imboassica Lagoon (Faria et al., 1998)	4.0 – 11.0	0.1 – 0.9
Cima Lake (Pedrosa, 1999)	30 – 90	0.5 – 2.0
Grussaí Lagoon (Suzuki, 1997)	65 – 200	4 – 17
***Vigario* Lake (VL1) - Wet period**	**270-443**	**8-10**
***Vigario* Lake (VL2) - Dry period (This study)**	**341-537**	**7-12**

Mesocosm experiment

The water retention time in the experimental mesocosms was around 10 days, similarly to the reported in the literature for other constructed wetlands (CRITES, 1994; HENCH et al., 2003; OLADEJO et al., 2015). The CW systems used here showed to be very effective on improving water quality, being dependent upon the sediment only, the aquatic macrophytes only, and on both the sediment and the macrophytes together.

Biochemical oxygen demand and total and thermotolerant coliforms were removed significantly in both vegetated and unvegetated wetlands, with a slightly higher removal being detected when macrophytes were present. The BOD removal of 84% in the vegetated wetlands is compatible to other studies using the macrophyte *Phragmites australis* (VYMAZAL, 2001) and *Pistia stratiotes* (OLADEJO et al,. 2015). This value was similar to the unvegetated wetlands because the main mechanism responsible for BOD removal is performed by biofilms associated to both the plant and the sediment (LIM et al., 2003). The slightly higher removal in the vegetated systems is due to the roots, which bring oxygen to the sediment through a process of convection flux (BRIX, 1994) and promote a high surface area for the colonization of microorganisms, both contributing to the diminishment of the BOD in the water.

Processes occurring mainly in the sediment were also responsible for the high removal rates of total (94%) and thermotolerant (87%) coliforms, nitrite, nitrate, total nitrogen, total dissolved phosphorus and total phosphorus, which were compatible to other studies. Mashauri et al. (2000) detected an average removal of 91% for total and 90% for thermotolerant coliforms in a large, multi-step constructed wetland in Tanzania using *Typha latifolia*, whereas Oladejo et al. (2015) measured a removal of nitrate by over 50% in small wetlands in Nigeria. This illustrates the important function of the wetland on water treatment, independently on the other additional steps of treatment. The main process responsible for both total and thermotolerant coliforms removal is related to the filtering action of the sediment, with an extra effect (though not significant in this study) of the macrophytes' roots. According to Ottová et al. (1997), the role of macrophytes on coliforms removal is due to the physical process of retention by roots associated to antibiotics produced by them.

Ammonium, inorganic dissolved nitrogen, total dissolved nitrogen and orthophosphate were highly removed in the vegetated wetlands. Here, *Typha domingensis* played a fundamental role on the depuration of the inflow waters. Ayaz and Akça (2001) studied several species of aquatic macrophytes on CWs using a surface continuous flow and concluded that aquatic macrophytes are important components of constructed wetlands, being responsible for the removal of 88% of ammonium and 48% of orthophosphate. On the other hand, three out of those four variables showed an increment in the unvegetated constructed wetlands in relation to the inflow waters. This can be explained by the lower EH and dissolved oxygen values in the unvegetated wetlands in relation to the vegetated ones (not significant), which could have caused ammonification and remobilization of phosphate from the sediment.

Conclusions

Despite being inserted in an essentially urban area and having received sewage disposal during several decades, the *Vigario-Taquaruçu* system keeps fundamental processes and functions that characterize lakes and wetlands. The wetland plays an important role on the cleanse of waters coming from the highly polluted *Vigario* Lake. However, this process could not be quantified *in situ* due to contamination on its margins. A mesocosm experiment further showed that both the sediment and the aquatic macrophytes in the wetland are important components for the maintenance of this system, significantly contributing to the depuration of the waters coming from the highly polluted *Vigario* Lake towards the *Taquaruçu* Lake.

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Appendix 1 – Chloride/Sulphate ratio calculated with the average values of chloride and sulphate showed in the Table 2.

NC = Not calculated

Chloride/Sulphate		
	Dry	Wet
VL1 SUR	44	46
VL1 BOT	29	26
VL2 SUR	31	40
VL2 BOT	NC	27
VLOC	48	32
WOC SUR	140	150
WOC BOT	121	160
TL SUR	37	35
TL BOT	37	36
TL1 SUR	50	54
TL1 BOT	35	50
TL2 SUR	42	34
TL2 BOT	44	29

Appendix 2 – Averages and coefficients of variation (n=17) of measured variables in the waters of inflow (Vigario Lake) and outflow (vegetated CWs T1, T2, T3; unvegetated CWs T4, T5, T6) of the experimental mesocosms. Biochemical oxygen demand (BOD, $mg.L^{-1}$), total coliforms (MPN), total coliforms (MPN), temperature (ºC), electric conductivity ($\mu S.cm^{-1}$), pH, redox potential (EH, mV), total dissolved solids (TDS, $mg.L^{-1}$), total alkalinity ($mEq.L^{-1}$), dissolved oxygen (DO, $mg.L^{-1}$), ammonium ($N\text{-}NH_4^+$, $mg.L^{-1}$), nitrite ($N\text{-}NO_2$-, $mg.L^{-1}$), nitrate ($N\text{-}NO_3$-, $mg.L^{-1}$), dissolved inorganic nitrogen (N-DIN, $mg.L^{-1}$), total dissolved nitrogen (N-TDN, $mg.L^{-1}$), total nitrogen (N-TN, $mg.L^{-1}$), orthophosphate ($P\text{-}PO_4^{3-}$, $mg.L^{-1}$), total dissolved phosphorus (P-TDP, $mg.L^{-1}$), total phosphorus (P-TP, $mg.L^{-1}$), dissolved organic carbon (DOC, $mg.L^{-1}$).

	Inflow	T1	T2	T3	T4	T5	T6
BOD	4.2(21)	0.5(12)	0.9(25)	0.6(22)	0.6(20)	0.8(21)	1.0(21)
Total coliforms	17000(0)	2200(0)	2100(0)	2100(0)	3400(0)	3300(0)	2700(0)
Thermot. coliforms	9000(0)	800(0)	800(0)	800(0)	1300(0)	1700(0)	1400(0)
Temperature	26(10)	27(10)	27(11)	27(10)	27(11)	27(11)	27(10)
Electric cond.	726(10)	1181(16)	1003(12)	982 (12)	920(13)	929(10)	894(16)
pH	8.2(7.0)	6.5(2.1)	6.7(3.2)	6.6(2.2)	6.9(2.0)	6.8(2.0)	6.8(5.0)
EH	159(17)	173(43)	171(35)	186(34)	155(60)	31(135)	38(105)
TDS	637(4)	1069(7)	898(5)	856(4)	784(5)	788(6)	801(5)
Total alkal.	2.6(9)	3.5(11)	3.3(17)	3.2(11)	2.6(14)	2.6(10)	2.7(14)
DO	8.1(58)	2.1(54)	2.0(61)	1.9(91)	1.8(77)	1.3(85)	1.2(92)
N-NH4+	0.16(131)	0.03(45)	0.03(47)	0.03(68)	0.28(60)	0.57(33)	0.54(32)
N-NO2-	0.02(83)	0.01(86)	0.01(60)	0.01(54)	0.01(32)	0.01(30)	0.01(27)
N-NO3-	0.11(178)	0.02(52)	0.02(78)	0.02(54)	0.04(56)	0.03(65)	0.02(63)
N-DIN	0.29(90)	0.05(28)	0.06(48)	0.05(40)	0.33(46)	0.61(29)	0.57(31)
N-TDN	2.59(38)	0.94(8)	0.96(7)	0.99(4)	1.19(21)	1.28(10)	1.30(10)
N-TN	3.8(24)	1.7(18)	1.6(12)	1.5(11)	2.1(11)	2.3(5)	2.6(7)
P-PO43-	0.04(66)	0.02(83)	0.01(34)	0.01(55)	0.05(68)	0.10(67)	0.09(51)
P-TDP	0.23(62)	0.05(28)	0.06(29)	0.06(29)	0.10(33)	0.14(29)	0.11(14)
P-TP	0.3(38)	0.1(25)	0.1(25)	0.1(27)	0.1(26)	0.2(24)	0.1(19)
DOC	16.8(45)	19.7(52)	16.2(34)	27.3(57)	23.5(48)	22.8(24)	21.3(29)