Nutrients retention in a small subtropical wetland (México)

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ABSTRACT

In tropical areas very few studies have analyzed wetlands' ability to control nutrients. We analyzed the efficiency of the Pátzcuaro subtropical wetland in Mexico to retain nutrients (total phosphorus: TP; soluble reactive phosphorus: PO_4^{3-}, nitrite: NO_2^- and nitrate: NO_3^-) and total suspended solids (TSS) and its temporal variability from November 2011 to October 2012, where two hydrological different periods (dry and wet periods) were included. The results indicate that, annually, this wetland reduced TP, 30.4%; PO_4^{3-}, 19.2%; NO_2^-, 2.5%; NO_3^-, 17.6%; and TSS, 14.7%. However, the reduction % rose to 55.3% for TP and to 47.3% for PO_4^{3-} during the dry period and to 14.1% for NO_2^-, 49% for NO_3^- and 44.5% for TSS during the rainy period. These results show dependence on the hydrological cycle, although P retention is also related with uptake by a dense macrophyte community and with organic matter accumulation. The results obtained suggest that removal of N is due mainly to denitrification. TSS retention seems to respond to low speed hydraulics and the resistance generated by macrophytes roots and floating plants. Like other studies in temperate environments, this wetland seems to remove more efficiently P than N. Unlike that in temperate environments where the highest nutrient retention occurs in autumn, we found the highest retention values for both NO_2^- and NO_3^- during summer (rainy period), and the lowest for P, probably due to release of P for the senescence of wetland plants during this period.

Key words: Nitrates; phosphates; total phosphorus; organic matter; hydrological periods; Pátzcuaro wetland.

INTRODUCTION

Wetlands are recognized as one of the world's most productive ecosystems (Costanza *et al*., 1997). Their ability to provide ecosystem services, such as supply (*e.g.*, food, water, raw materials, *etc*.), regulation (*e.g.*, carbon storage, control of erosion, natural disturbances, *etc*.) and cultural (*e.g.*, recreational activities, environmental education) has been internationally acknowledged (Millennium Ecosystem Assessment, 2005; Zak *et al*., 2011; McInnes, 2013). Among these services, emphasis is placed on high self-purification capacity to control nutrient and sediment dynamics, minimise eutrophication effects and contribution to water quality maintenance (Johnston, 1991). In fact, wetlands are recognised for their ability to retain, transform and assimilate nutrients (Mitsch, 1992; Woltemade, 2000; Hoffmann *et al*., 2009), although the mechanisms by which nutrients and organic matter are retained are still not fully understood (Fisher and Acreman, 2004).

Nutrients like nitrogen and phosphorus are essential for plant growth, but excessive concentrations can trigger algae blooms, limiting light penetration, and lower the dissolved oxygen concentration, which eventually develop into surface waters (rivers, lakes, reservoirs) eu-

trophication (Vitousek *et al*., 1997; Smith, 2003). Therefore, retention of nitrogen and phosphorus in wetlands can benefit the water bodies associated with them by improving the quality of the water (Johnston, 1991; Fisher and Acreman, 2004). Excessive nutrients discharges, from both point sources (*e.g.*, direct discharges and industrial organic) and diffuse sources through runoff from agricultural lands, have been accepted as one of the most important causes of pollution problems and aquatic ecosystem eutrophication in the world (Conley *et al*., 2009; García-García *et al*., 2013; Kopacek *et al*., 2013). Several studies have shown that small wetlands can act as sinks for nutrients by controlling non-point sources of pollution in agricultural areas, and have demonstrated their natural potential to control water quality (Knox *et al*., 2008; García-García *et al*., 2009, 2013). However, their retention capacity depends on the type of nutrients that arrive at the wetland. Different studies have revealed that the majority of the wetlands that reduce nutrients discharge present different percentages of nitrogen and phosphorus reduction rates (Johnston, 1991). Nitrogen is easily removed *via* denitrification under anaerobic conditions, besides biological uptake and microbial immobilization (Vymazal, 2007). Yet there is evidence that wetlands are less efficient at retaining soluble phosphorus (Hoffman *et al*., 2012)

and in wetlands dominated by surface water flow, such as Pátzcuaro wetland, is controlled by physical, geochemical and biological processes (Sabater *et al.*, 2003; Hoffman *et al.*, 2009). In addition, this retention can be affected by the hydrological cycle phase (AlMaarofi *et al.*, 2013). Broadly, reduced nutrients retention from wetlands occurs frequently in autumn in temperate areas to coincide with the periods of highest precipitation and increased water flows (Fisher and Acreman, 2004). Nitrogen retention efficiency tended to increase during summer months due mainly biological uptake and denitrification (Garcia-Garcia *et al.*, 2009). In relation to phosphorus, Reddy *et al*. (2010) suggest that during dry period retention of phosphorus depending to abiotic characteristics of sediment wetland. So, four processes can be involved in phosphorus retention: adsorption to the exchangeable complex; precipitation joined to Ca, Mg or carbonates; adsorption to Fe oxides and absorption to aquatic plants (Alvarez-Rogel *et al.*, 2006).

In general, information available on natural tropical wetlands is very fragmented and has been developed fundamentally from descriptive approaches (*e.g*., physicochemical characterization, floristic and faunistic inventories, and human impacts) (Junk, 2002). Very few studies have analyzed functional aspects such as wetlands' ability to control nutrients. On the contrary, the few studies that actually exist have been conducted mostly in artificial wetlands (Vymazal, 2007). Despite the important ecoservices that wetlands generally provide to the human population, tropical and subtropical wetlands are increasingly threatened because of higher population density, increasing demand for water and land, and also because many are relatively small (Junk, 2002). In Mexico, around 62.1% of wetlands, including brackish, marine and freshwater wetlands, have been lost (Landgrave and Moreno-Casasola, 2012) despite the existing legal framework to promote wetland conservation and sustainable use (Morzaria-Luna *et al*., 2014).

The subtropical Lake Pátzcuaro wetland, declared a RAMSAR site in 2005 (No. 1447), is considered a buffer zone that receives significant runoff, which contributes to maintain the water level and the water and biological quality of Lake Pátzcuaro (Chacón-Torres and Múzquiz-Iribe, 1997). This wetland supports the local economy of many indigenous populations, such as raw material (vegetation) for craft activities, besides tourism, fishing and forestry (Chacón-Torres, 1993; Bernal-Brooks, 2002; García-Villanueva, 2007). Recently, progressive wetland deterioration has been detected by the pressure that anthropogenic activities in the region cause (mainly deforestation, land-use change to agriculture, livestock rearing, and organic effluents) (Bravo-Inclán *et al*., 2012). Yet despite the importance of this wetland for maintaining its water quality, there are no studies that quantify its poten-

tial for retaining nutrient. So, the main objectives of this study are to: i) quantify retention capacity for the nutrients (nitrates, NO_3^-; nitrites, NO_2^-; soluble reactive phosphorus, PO_4^{3-}; total phosphorous) of the South Lake Pátzcuaro wetland over an annual cycle; ii) analyze the effects of temporal hydrological variability on nutrients retention; iii) examine the effect of environmental factors on nutrients retention.

METHODS

Study area

This study was carried out in a subtropical wetland located in the Mexican State of Michoacán within the Mexican transvolcanic Belt in the Lake Pátzcuaro-Cuitzeo basin, where Lake Pátzcuaro watershed is located. This wetland covers 707 hectares and lies between UTM coordinates X=246175.12, 204562.47 (East longitude), and Y=2171501.92, 2145020.65 (North latitude) at an altitude of 2036 m asl (Fig. 1). This wetland is associated with the south Lake Pátzcuaro (13,000 hectares), and is surrounded by a series of hills and volcanoes following an altitudinal profile in a southern direction. The wetland is located in the foothills of La Taza volcano (2339 m asl), a geological unit dominated by *malpaís*, and a vast valley of agricultural land, in which the former island of Jarácuaro was formed by lake sediments (Garduño-Monroy *et al.,* 2009). The slope of the basin is abrupt and at a short distance to the wetland, with a plain whose slopes are less than 3%, and hills of volcanic material that favor surface runoff and carry solid materials, which cause siltation and the shallowness of the wetland (Bischoff *et al*., 2004). The climate is temperate humid with summer rains and less than 5 mm of winter rainfall (INEGI, 2008a). The wetland is crossed by a series of artificial navigation channels, used by the human communities around the lake. It should be emphasized that there are no permanent streams in the study area (Fig. 1). Therefore, any water flow to the wetland is produced basically by runoff (INEGI, 2008b) and probably by shallow ground-water flows, which occur primarily in the summer rainy season (Bischoff *et al*., 2004). The wetland is shallow, its maximum depth does not exceed 150 cm, and the water velocity is practically zero (0.05 cm s⁻¹) (Ayala *et al*., 2008). However the wetland does not dry and a shallow layer of water remains during the dry season. The soils near the wetland have a sandy and loamy texture. They are easily erodible and slightly acidic, and are associated with the volcanic origin of the region, represented mainly by andosols and luvisols (Vargas *et al*., 2000; Bravo-Espinoza *et al*., 2006). We have not detected peat in the wetland. About 19% of the wetland is used to agriculture and almost 46% is occupied by the Jarácuaro Island where some villages exist. Surrounding wetland there are wooded pine oak areas (Huerto-Delgadillo and García, 2011). Besides livestock is

an important activity in the wetland. To the south of Lake Pátzcuaro, a progressive silting process is underway, caused by deforestation and inappropriate agricultural practices, including use of agrochemicals (Rojas, 2002), which give rise to the input of contaminants from such activities, and the wastewater from nearby villages also contribute (Vargas *et al.*, 2000). A diverse and dense macrophytes community covers the wetland including emerging macrophytes (*Thy-*
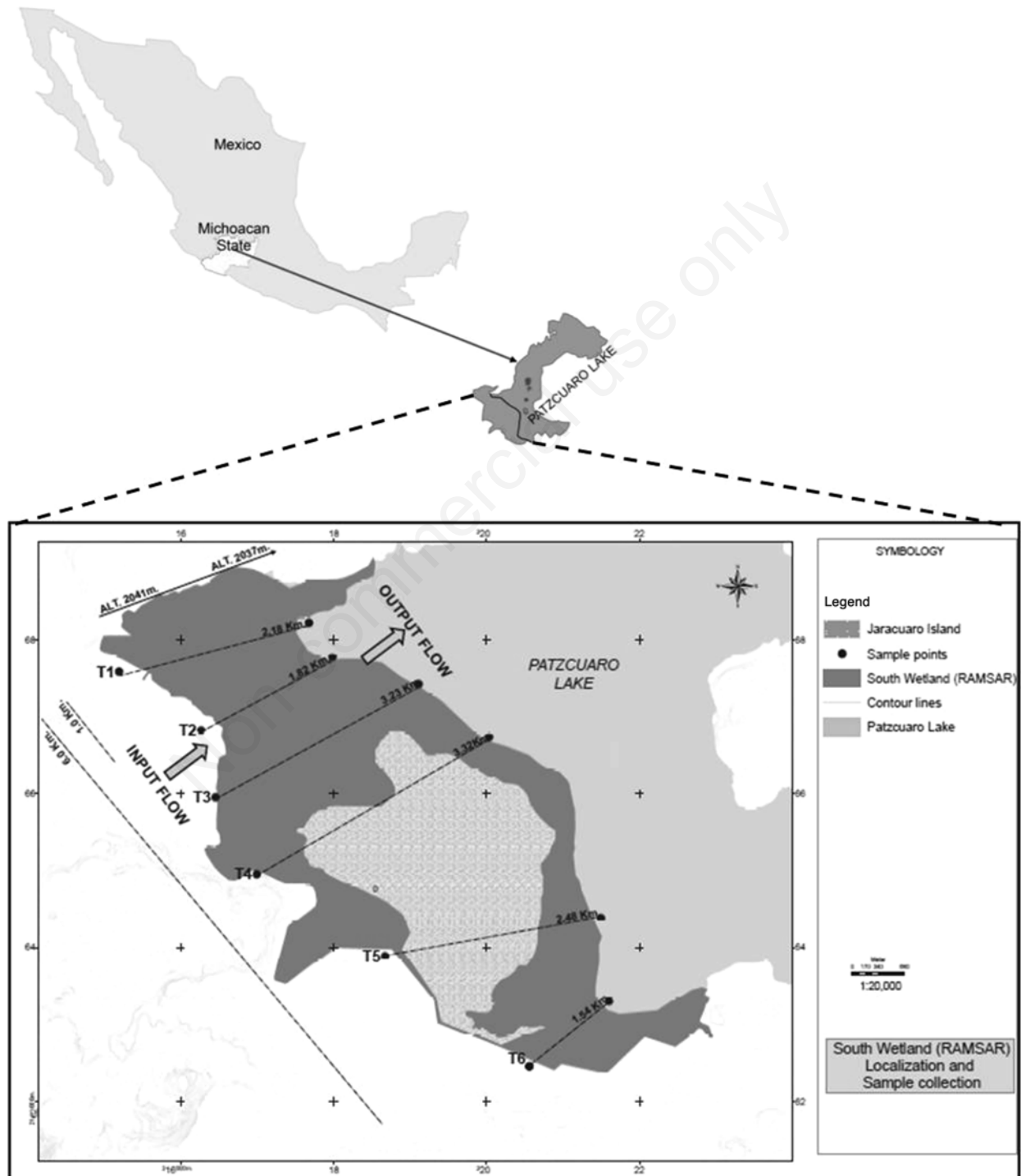

Fig. 1. Location of the South Lake Pátzcuaro wetland and sampling points. T1, T2, T3, T4, T5 and T6 represent the transects where samples were collected.

pha dominguensis, Schoenoplectus californicus and *Phragmites australis*), floating leaves (*Nymphaea mexicana)*, and submerged (*Potamogeton illinoesis* and *P. pectinatus*) and free floating (*Eichhornia crassipes* and *Oxycarium cubense*) (Bernal-Brooks *et al.*, 2003). The practice of burning and conditioning the land for agricultural use is commonplace in the wetland (Huerto-Delgadillo and García, 2011).

Although there are no previous physico-chemical characteristics data of the water in the wetland, some studies indicate that the waters of the Southern area of Lake Pátzcuaro, where leads the wetland, are alkaline (332 mg CaCO$_3$ L^{-1}), pH slightly alkaline, conductivity of 714.5μS cm^{-1}, with a high concentration of nitrogen (total nitrogen=2.44 mg L^{-1}) and phosphorous poor (TP=0.21mg L^{-1}), BOD$_5$ of 15 mg L^{-1}, and TSS of 668.49 mg L^{-1} (Sánchez-Chávez *et al.*, 2011).

Sample collection

Based on the Ramsar Wetland, south of the Pátzcuaro polygon (707 ha) and the wetland hydrological map scale 1:20; six transects were established from southwest to northeast direction. In each transect, two sampling points were selected based on (Fig. 1), which resulted in 12 points. The sampling points located at the beginning of each transect collected monthly (12 months) on the entry of water to the wetland watershed runoff (input), while the terminals were placed at the edge of Lake Pátzcuaro (output). The linear distance covered by each transects depended on its location; the maximum distance was 3.32 km in Transect 4, and the minimum distance was 1.54 km in Transect 6. The average gradient at the beginning of each transect was 2.2% and 0.2% at the end. Sample collection was conducted from November 2011 to October 2012 (12 sampling months), and 144 samples were obtained from the two periods: the dry period, from November to May; the rainy period from June to October (Fig. 1). During the dry period, accumulated precipitation was 80 mm, with an average runoff of 100.08 m^3. During the rainy period, precipitation was 794.2 mm, and 1488.98 m^3 of runoff, with maximum rainfall of 325 mm in August (Fig. 2). In the field, water temperature, pH and conductivity (Conductronic model PC18, previously calibrated and equipped with a conductivity cell, pH electrode and integrated thermistor) were recorded for each sample site. Dissolved oxygen (DO) was recorded with previously calibrated and Winkler-modified yellow spring multiparametric equipment (Eaton *et al.*, 1995). Moreover, surface water samples were collected and stored in polyethylene containers (capacity of 4 L), were previously treated with 10% hydrochloric acid and rinsed with distilled water. These samples were transported to the laboratory in cold storage and filtrated (Whatman GF/F, with a pore size of 0.7 μm) for the subsequent analysis of nu-

trients (NO$_3^-$, NO$_2^-$, PO$_4^{3-}$, and TP), except for TSS and the BOD$_5$ and COD.

Chemical analysis

Water samples were analyzed in triplicate in 24 h. Determination of TP was carried out by the phosphomolybdate technique (Murphy and Riley, 1962), with prior digestion in a semi-automated autoclave. For PO$_4^{3-}$, the ascorbic acid technique was used (Eaton *et al.*, 1995). NO$_2^-$ was determined by the sulfanilamide hydrochloride solution technique, and NO$_3^-$ was established by the brucine acid technique (Eaton *et al.*, 1995). The four variables were measured by a colorimetric method using a spectrophotometer, the Perkin Elmer Lambda 10UV/Vis model, after obtaining the calibration curves to calculate the corresponding concentrations. BOD$_5$ was determined with the incubation technique and COD by the concentrated sulfuric acid digestion technique (Eaton *et al.*, 1995). TSS were estimated by the gravimetric technique after filtering water samples with glass fiber filters (Whatman International Ltd., GF/C with a pore size of 0.45 μm), to be then dried at 105°C and weighed in an analytical balance to obtain a 0.01 mg reading of precision (Strickland and Parsons, 1972). During the study, the chloride (Cl$^-$) concentration was not analyzed. However, bibliog-
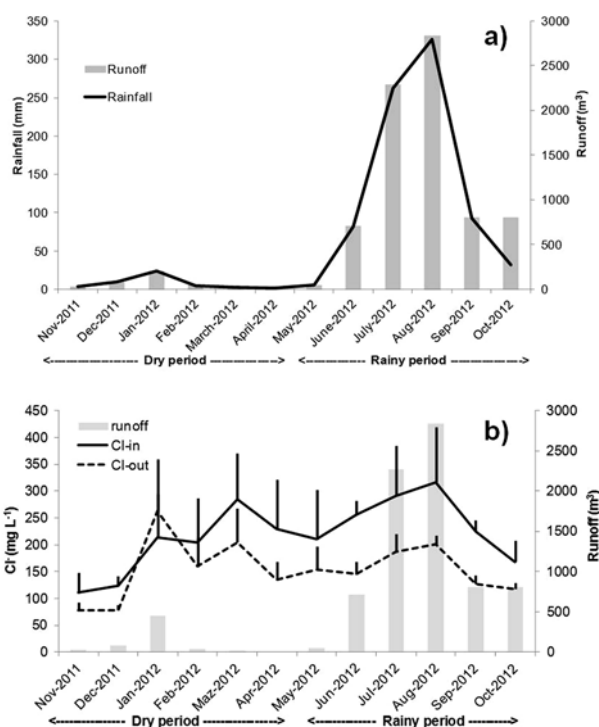

Fig. 2. Annual precipitation and runoff (a), and input and output of chloride (Cl$^-$) concentrations (mean +SD) (b), during the study period at the South Lake Pátzcuaro wetland.

raphy data (Bischoff *et al*., 2004) from technical reports (SEPLADE, 2000; Aguillón *et al*., 2006) and our own data collected in south Pátzcuaro Lake area and at several points around the wetland were employed. These data covered a long period from 1999 to 2009. Due to the high correlation between conductivity and Cl^- concentration ($R^2= 0.96$; P<0.01; n=25), the Cl^- concentration for all the chloride samples was calculated with this equation: y=0.2037x-84.036.

Retention calculations

Since there were no permanent streams that feed the wetland, surface runoff was calculated each month (12 months) by the indirect method of the monthly runoff (Q in $m^3 s^{-1}$) that the wetland receives from precipitation, without considering the interception of rain by vegetation and soil moisture. Calculation of the average surface runoff in the area is based on the estimate of the surface runoff from rain (P) in mm that occurs in the study area (A) km^2 by applying a runoff coefficient (C), which varied from 0.1 to 1.0 depending on slope, soil texture (clay loam in our case) and land use. Finally, a correction factor of units (F=0.028) was applied in m^3 (F is a numerical constant of the resulting units which the variables are expressed) (Treviño *et al*., 2002; Viera-Briones *et al*., 2012) with the following equation:

$$Q=A * C * P * F \qquad (eq. 1)$$

Cl^- was used as a passive indicator as it undergoes dispersion, dilution and dissemination, but it is not easy to remove from solutions. Hence variations in the Cl^- concentration allow the detection of possible dilution *via* lateral or subsurface water inputs or by the evapotranspiration concentration, which can alter the concentrations of nutrients and other elements (García-García *et al*., 2009). So retention (%R), understood as the elimination percentage of different forms of nutrients (NO_3^-, NO_2^-; PO_4^{3-} and TP and TSS), was calculated on each sampling date by considering the difference between the relationship of the input concentrations (Nutrient/Cl^-_{in}) and the output concentration (Nutrient/Cl^-_{out}) in the wetland (Fleischer and Stibe, 1991; Jordan *et al*., 2007) following the formula (Trudell *et al*., 1986):

$$\%R=(1- (Nutrient/Cl^-_{out}/Nutrient/Cl^-_{in})) \times 100) \qquad (eq. 2)$$

A positive retention value means that the inflow Nutrient/Cl^- ratio was higher than the outflow Nutrient/Cl^- ratio, indicates that the wetland acts as a sink of nutrients. On the contrary, a negative retention value means that the outflow Nutrient/Cl^- ratio was higher than the inflow Nutrient/Cl^- ratio, indicates that the wetland acts as source of nutrients.

Statistical analyses

For the statistical analyses, the Minitab 16 software for Windows (Minitab Inc., State College, PA, USA) and SPSS (software ver. 19 for windows; SPSS Inc., Chicago, IL, USA) were used. To quantify the temporal variability of the input and output concentrations in the wetland of the different forms of nutrients (NO_3^-, NO_2^-, PO_4^{3-} and TP) and TSS, the coefficient of variation (CV %) was calculated. An analysis of variance (one-way ANOVA) was used for a factor (P=0.05) followed by a Tukey's test with a 95% confidence interval to determine annual and seasonal differences in the retention percentage (%R) during the dry (November-May) and rainy (June-October) periods, and the temporal variability in the wetland's environmental parameters. Finally, Spearman correlations analysis was applied to obtain the coefficient of correlation between %R and the environmental variables in the wetland. Whenever necessary, the input and output nutrients concentration data were log (x+1)-transformed to ensure normality and homogeneity of variance.

RESULTS

Seasonal characterization of inflow and outflow water

The total runoff received by the wetland was 7899 m^3. During the rainy period, runoff was higher (7445 m^3, n=5 months) than during the dry period (453.8 m^3, n=7 months). The maximum value was recorded in August (2835 m^3) and the minimum one was recorded in April (11.4 m^3) (Fig. 2). The ANOVA test did not show statistical differences between runoff and Cl^- concentration (both input and output; F=3.30, P>0.05) throughout the year. The annual mean input Cl^- concentration value was higher (219.45 mg L^{-1}) than for output (154.33 mg L^{-1}). The input and output Cl^- concentrations followed the same trend throughout the study period (Fig. 2), except in January when atypical precipitation was recorded, although they showed greater temporal variability (CV_{in}=41.04 and CV_{out}=42.13, n=12, respectively; Tab. 1), which was maintained during both periods (CV_{in}=32.16, CV_{out}=25.22 for the rainy period; CV_{in}=45.86, CV_{out}=51.46 for the dry period; Tab. 2). The mean values for input water temperature, pH and conductivity were similar to the output ones (Tab. 1) and they all showed temporal variability (CV<30%), although statistically significant differences between input and output conductivity were found (F=24.74, P=0.01). These variables maintained the same pattern during the rainy and dry periods (Tab. 2). Water temperature presented a low coefficient of variation in both the rainy and dry periods (Tab. 2). Similarly, a low variability was recorded for pH in both periods (Tab. 2), although a significant difference (F=4.50, p=0.014) was detected between input and output during the rainy period. DO concentrations, BOD_5 and COD showed low variabil-

ity, for both input and output, during the study period (Tab. 1). DO showed the highest variability during the rainy period (CV_{out}=49.62%, Tab. 2) and a significant difference was detected between input and output (F=6.13, p=0.009). Likewise, significant differences were observed between input and output for BOD_5 and COD (F=569.61, P=0.001) during the rainy period. The BOD_5 values were always higher in inflow than in outflow, except for November and the end of the dry period (April and May) (Fig. 3). The inputs TSS were always higher than for output in both periods (Tab 2, Fig. 3). Regarding nutrient concentrations, the mean annual values for the input TP and PO_4^{3-} concentrations in the wetland were almost 2-fold higher than for output (Tab. 1), with higher temporal variability found for output (CV=67.3% and CV=67.57%) than input (CV=38.1% and CV=40.76%) (Tab. 1). Highest TP concentrations were found for input during the rainy period (Tab. 2), while the lowest were for output during the dry period (Tab. 2). This same trend was shown by the PO_4^{3-} concentrations (Tab. 2), except in July (237.95 µg L^{-1}) and August (166.56 µg L^{-1}), when a higher PO_4^{3-} concentration was reported in output than in input (Fig. 3). ANOVA test indicated that TP (F=32.99, P=0.001) and PO_4^{3-} (F=18.39, P=0.007) differed significantly during the rainy and dry periods.

The mean annual value for NO_2^- inputs was 50% higher than output (Tab. 1), and the coefficient of variation for NO_2^- was greater (CV_{in}=75.41% and CV_{out}=52.85%) than that reported for NO_3^- (CV_{in}=49.84% and CV_{out}=45.49%) (Tab. 1). Both the NO_2^- and NO_3^- concentrations presented significant differences between input and output (F=21.95 and 85.85 respectively, p<0.05) and between rainy and dry periods (F=12.13, P=0.001; F=22.47, P=0.001). In both the rainy and dry periods, the mean input NO_3^- concentrations were higher than for out-

put (Tab. 2). The NO_3^- concentrations were always higher for inflow than for outflow, except at the end of the dry period (April and May) (Fig. 3).

Nutrients retention

When considering all the sampling data, the mean annual retention (%R) for TP was 30.35%, and the mean maximum retention was reported during the dry period (Tab. 3). Similarly, the mean maximum %R for PO_4^{3-} was obtained during the same period (Tab. 3). The net mean retention was 47.12% (n=54) for TP and 43.87% (n=48) for PO_4^{3-}, while no retention of TP occurred on the 18 sampling dates (mean export: -19.93%), nor of PO_4^{3-} on the 24 sampling dates (mean export: -30.16%) (Tab. 3). The mean annual retention for NO_2^- was very low and was a negative mean value during the dry period (-5.90%, n=42) (Tab. 3). On 31 sampling dates (40% of all samples), no retention of NO_2^- took place (mean export: -48.50%; Tab. 3). The mean annual retention for NO_3^- was 17.56%, with a maximum mean retention value recorded during the rainy period (48.99%, n=30). The net retention for NO_3^- was 38.76% (n=60), although the percentage of export was -88.41% (n=12). The mean annual retention for TSS was positive (14.68%) and the highest mean retention value was detected during the rainy period (Tab. 3). The mean value of net retention for TSS was 34.03% (n=52). The temporal variability of the retention for TP and PO_4^{3-} showed the same annual trend (Fig. 4), although the % R for TP presented less variability (CV=42.9%) than for PO_4^{3-} (CV=66.5%).

During the dry period, the %R for both parameters was positive, with a maximum of 82.19% for PO_4^{3-} in January and of 69.59% for TP in November. Positive retention values were detected for both parameters in October, at the end of rainy period (20.05% for TP and 19.74% for

Tab.1. Mean, maximum and minimum values of the different physico-chemical parameters measured in the input and output water of the South Lake Pátzcuaro wetland.

N=72	Input				Output			
	Mean±SD	Max	Min	CV (%)	Mean±SD	Max	Min	CV (%)
Water temperature (°C)	21.26±4.45	32.60	14.00	20.91	20.67±4.27	29.38	10.50	20.65
pH	8.09±0.47	9.70	7.00	5.83	8.25±0.45	9.00	6.93	5.47
Conductivity (µS cm^{-1})	1489.86±442.14	2860.00	702.00	29.68	1170.20±319.22	2545.90	672.00	27.28
Cl^- (mg L^{-1})	219.45±90.06	498.50	59.00	41.04	154.33±65.02	434.57	52.85	42.13
DO (mg O_2 L^{-1})	6.02±2.02	12.00	2.90	33.45	5.21±1.94	9.17	1.30	37.19
TP (µg L^{-1})	534.30±203.60	1156.00	70.20	38.10	236.20±159.00	1001.00	31.30	67.30
PO_4^{3-} (µg L^{-1})	198.64±80.96	416.80	30.30	40.76	107.58±72.69	409.20	3.79	67.57
NO_2^- (mg L^{-1})	0.10±0.07	0.38	0.02	75.41	0.05±0.03	0.16	0.01	52.85
NO_3^- (mg L^{-1})	7.81±3.89	24.49	0.03	49.84	3.61±1.64	10.73	0.20	45.49
BOD_5 (mg O_2 L^{-1})	245.60±81.12	483.10	77.82	33.03	211.78±59.31	379.33	77.82	28.00
COD (mg O_2 L^{-1})	944.53±254.30	1498.00	480.00	26.93	969.10±149.40	1200.40	280.00	15.42
TSS (mg L^{-1})	416.85±144.30	1009.00	10.80	34.63	228.00±108.70	800.00	7.30	47.66

PO_4^{3-}), and in June for TP (16.77%; Fig. 4). The highest export values were found during the dry period (-36.99% for TP in July and -47.94% for PO_4^{3-} in June).The NO_2^- retention values showed the highest temporal variability of all the nutrient forms (CV=122.1%). NO_2^- retention remained below the NO_3^- retention values almost all year, except in May (48.22%) and October (66.61%), when the highest NO_2^- retention values were reported. The wetland retained NO_3^- throughout the year, except at the end of dry period (-93.51% in April and -83.3% in May) (Fig. 4). The highest NO_3^- retention value was detected in November (72.89%). TSS showed high temporal variability (CV=99.4%). TSS were retained almost all year, except for three months during the dry period (November, December and April). The maximum TSS retention value was recorded in October (63.02%; Fig. 4).

Relationships between nutrients retention and environmental factors

During the rainy period, TP retention correlated positively with input TP concentration and input TSS, and negatively with conductivity and input BOD_5, while it correlated positively with input TP and negatively with input BOD_5 during the dry period (Tab. 4). PO_4^{3-} retention correlated positively with input for both DO and NO_2^- during the rainy period (P<0.05), and correlated negatively with pH and conductivity. During the dry period, PO_4^{3-} retention positively correlated only with TP input (P<0.05). (Tab. 4). NO_2^- retention correlated positively with the input for both NO_2^- and PO_4^{3-} during the rainy period and with the input DO and NO_2 concentrations during the dry period. Moreover, it correlated significantly and negatively with pH, water temperature and TSS input during the dry period, and only with TP input during the rainy period. NO_3^- retention correlated significantly and positively with the input for both the NO_3^- and NO_2^- concentrations during the dry period. Furthermore during this period, it correlated negatively with the inputs for both PO_4^{3-} and COD and also with conductivity and TSS input during the dry period (Tab. 4). TSS retention correlated only negatively with conductivity during the rainy period, while it correlated positively with this parameter during the dry period and negatively with water temperature, NO_2^- and NO_3^- inputs.

DISCUSSION

The south Pátzcuaro Lake wetland, like other subtropical lakes and wetlands of high altitudes (Challenger, 1999; Bauer, 2005), presents two distinctively marked hydrological periods: a shorter rainy period (5 months) and a dry long-term period (7 months). However, unlike other subtropical wetlands that remain completely dry during an annual hydrological cycle phase (Neiff, 2001),

Tab. 2. Mean, maximum and minimum values of the different physico-chemical parameters measured in the input and output water of the South Lake Pátzcuaro wetland during the rainy period (June-October) and the dry period (November-May).

| | Input | | | | | | | | Output | | | | | | | |
| | RAINY PERIOD (n=30) | | | | DRY PERIOD (n=42) | | | | RAINY PERIOD (n=30) | | | | DRY PERIOD (n=42) | | | |
	Mean±SD	Max	Min	CV (%)	Mean±SD	Max	Min	CV (%)	Mean±SD	Max	Min	CV (%)	Mean±SD	Max	Min	CV (%)
Water temperature (°C)	20.88±6.08	32.6	10.5	29.12	23.70±3.08	29.51	18.98	13.01	19.45±4.97	29.39	10.5	25.25	21.57±3.50	27.85	12.74	16.26
pH	7.97±0.64	9.0	6.93	7.97	8.17±0.29	8.69	7.59	3.5	8.31±0.36	9.0	7.6	4.38	8.21±0.50	8.99	6.93	6.14
Cond (µS cm⁻¹)	1647.70±397.20	2860	1073	24.11	1377.14±442.34	2500	702.0	32.12	1176.90±192.80	1541.6	922.8	16.38	1165.40±387.40	4245.9	672	33.25
Cl⁻ (mg L⁻¹)	251.60±80.60	498.5	134.5	32.16	196.49±90.10	425.21	59.0	45.86	155.70±39.27	229.99	103.93	25.22	153.40±78.90	434.6	52.90	51.46
DO (mg O₂ L⁻¹)	6.37±2.64	12.0	2.9	38.68	5.77±1.60	11.17	3.13	27.85	4.70±2.33	8.93	1.44	49.62	5.57±1.52	9.17	1.30	27.37
TP (µg L⁻¹)	626.90±231.10	1156	259.9	36.86	468.20±152.40	765.99	70.2	32.55	384.90±136.20	1001	278.3	35.39	130.01±53.97	227.97	31.31	41.51
PO₄³⁻ (µg L⁻¹)	215.10±77.10	416.8	94.7	35.79	186.90±82.53	390.0	30.3	44.16	162.40±68.80	409.2	55.8	42.37	68.42±45.04	201.22	3.79	65.83
NO₂⁻ (mg L⁻¹)	0.13±0.09	0.38	0.03	67.23	0.068±0.04	0.17	0.02	58.54	0.05±0.02	0.98	0.02	42.41	0.05±0.03	0.16	0.01	60.06
NO₃⁻ (mg L⁻¹)	9.51±4.65	24.49	0.03	48.83	6.60±2.71	13.14	3.0	41.05	3.46±1.46	5.99	1.09	42.33	3.72±1.77	10.73	0.20	47.54
BOD₅ (mg O₂ L⁻¹)	303.20±82.00	483.1	216.3	27.03	204.49±49.88	298.73	77.82	24.39	216.43±39.25	299.96	129.57	18.13	208.50±70.50	379.30	77.8	33.83
COD (mg O₂ L⁻¹)	815.10±232.04	1491	480	28.47	1036.00±230.10	1498	710.0	22.21	969.50±102.70	1181	700	10.59	968.70±176.70	1200.4	280	18.24
TSS (mg L⁻¹)	493.70±147.90	1009	240	29.96	362.01±114.90	598.9	10.8	31.74	165.10±72.60	398.1	7.3	43.96	272.90±108.40	800.0	122.6	39.74
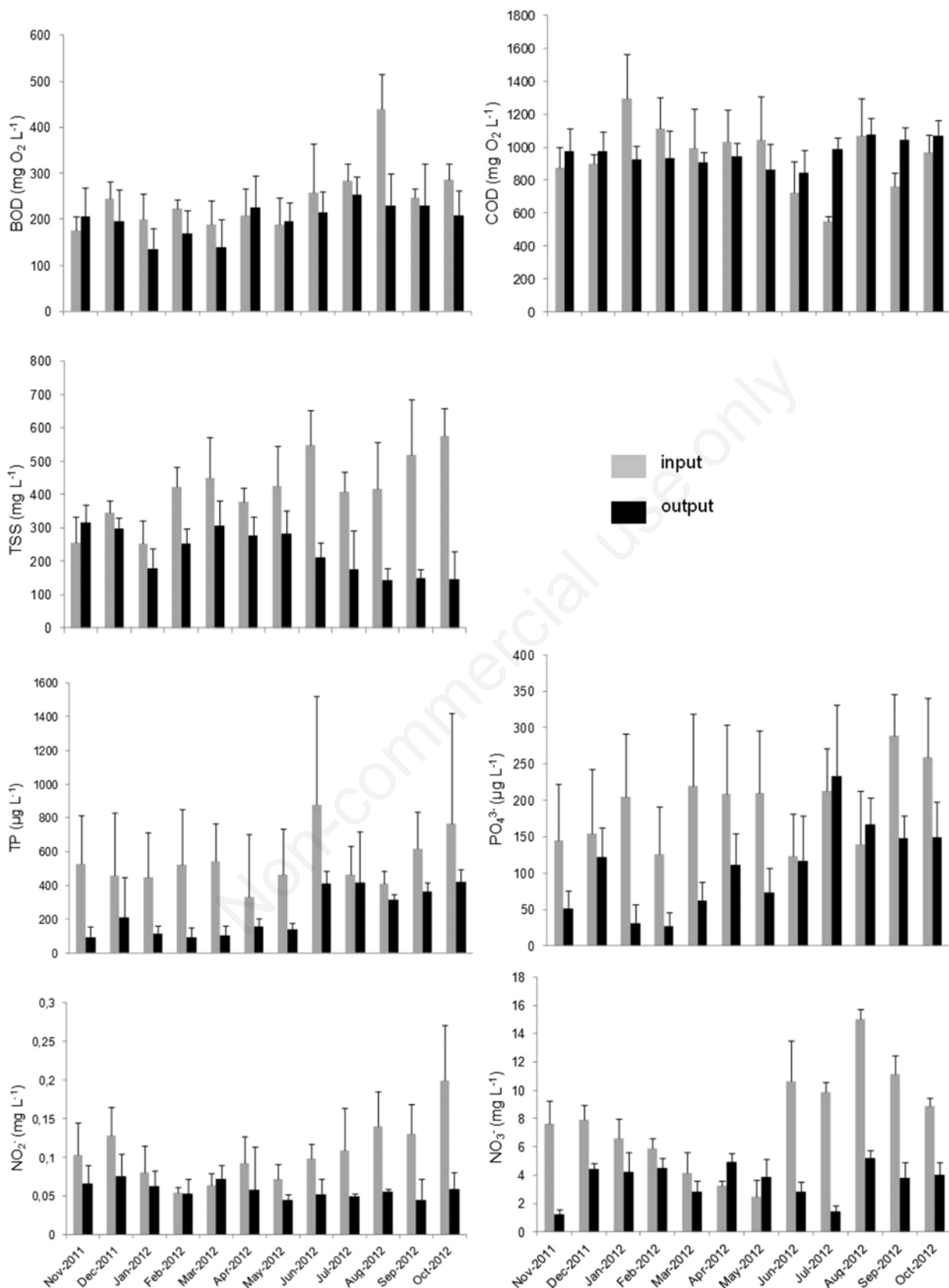
Fig. 3. Annual variation of the input (grey bars) and output (black bars) of BOD_5, COD, TSS, TP, PO_4^{3-}, NO_2^- and NO_3^-, concentrations (mean±SD) for the South Lake Pátzcuaro wetland.

Pátzcuaro wetland maintains surface water throughout the year in spite of a long dry period. Since this wetland has no streams that provide a water surface flow, water comes from indirect natural recharge through rainfall runoff (Ruiz, 2003), which is characteristic of high altitude areas, igneous metamorphic soil and weather conditions (Alcalá and Custodio, 2008), which is the case of the Pátzcuaro wetland. Therefore during the rainy period, the wetland accumulates about 94% of total annual rainfall runoff (Fig. 1), which allows a constant layer of water to remain
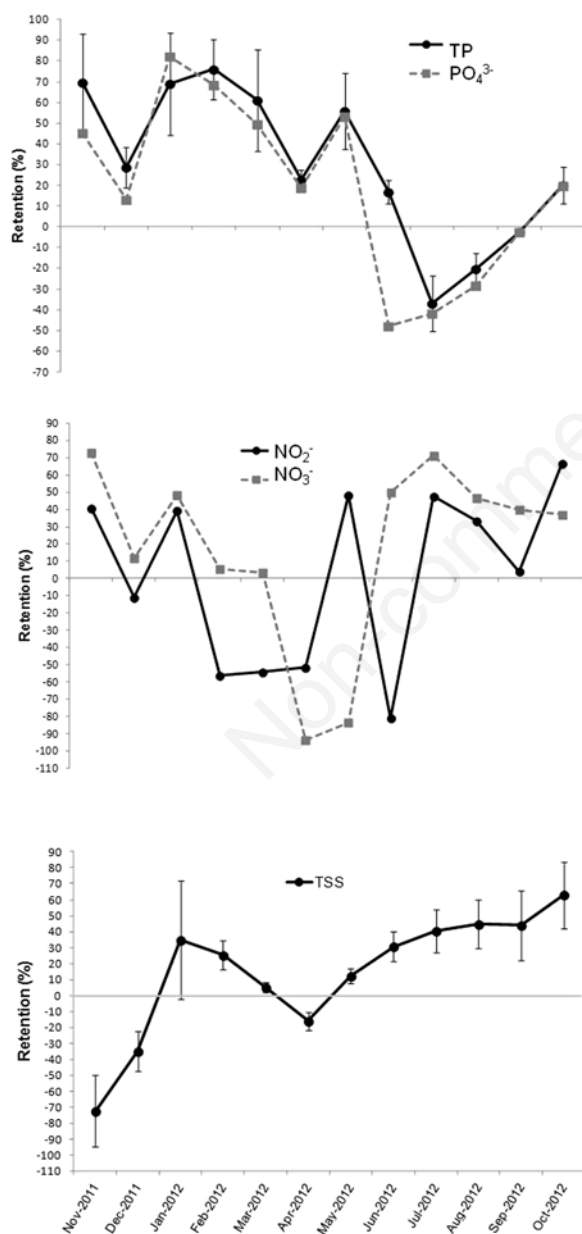
throughout the year. Indeed precipitation is the main source for maintaining the water table in the wetland. However other sources, such as lateral or subsurface water inputs or losses like evapotranspiration, can be important factors that explain the hydrological dynamics of wetlands (Sabater *et al.*, 2003). As chloride is a conservative element (Álvarez-Rogel *et al.*, 2006), Cl^- concentration was used as an indirect indicator to detect possible water inputs and/or outputs to wetlands (Simmons *et al.*, 1992; Sabater *et al.*, 2003). Our results indicate that Cl^- concentration in inflow was always higher than in outflow (except January because of atypical rain, Fig. 2). Thus we assumed that the dilution caused by the inflow of subsurface water diffuse or by discharges from springs was not found to be relevant and did not affect nutrient concentration. The South Lake Pátzcuaro wetland has proved to efficiently lower nutrient concentrations (TP, PO_4^{3-}, NO_2^- and NO_3^-), although its effectiveness differs depending on the nutrient species and the period of year considered (Schade *et al.*, 2002; Vellidis *et al.*, 2003). We found a mean annual reduction of 30.35% for TP and 19.19% for PO_4^{3-}, but these reductions increase significantly during the dry period (55.32% for TP and 47.3% for PO_4^{3-}; Tab. 3). On the contrary, both forms were exported during the rainy period. These retention values are similar to those reported in the literature. According to Kadlec and Knight (1996), mean retention percentages by constructed wetlands receiving municipal wastewaters were 34% for TP and 41% for PO_4^{3-}. Mitsch *et al.* (1995) found that the average TP concentration decreased by 64-92% in four constructed freshwater riparian marshes of low flow in northeastern Illinois. In a Louisiana forested waste-water treatment wetland, Blahnik and Day (2000) reported highly variable retention values for PO_4^{3-} (3-50%). Knox *et al.* (2008) obtained reductions of 35% and 42% for TP and PO_4^{3-}, respectively in a natural wetland situated in Northern California.

The pattern of retention followed by the two N forms differs. The highest mean annual reduction is reported for NO_3^- (17.56%), whereas annual NO_2^- reduction is only 2.45%. However, unlike TP and PO_4^{3-}, NO_3^- reduction increased significantly during the rainy period to 48.99%. In general, these retention values are lower than those reported in the literature. In a forested wetland of Louisiana, Blahnik and Day (2000) found retention NO_3^- to lie between 32% and 95%; Knox *et al.* (2008) reported a 60% reduction in a Californian wetland, and studies into riparian forests have indicated high retention for NO_3^- (over 80%; Lowrance *et al.*, 1984; Jordan *et al.*, 1993). For TSS, we obtained mean annual retention values of 14.68%, but this retention increased to 44.52% during the rainy period. During the dry period, the wetland exported TSS (mean: -6.63%). These reduced TSS values are lower than those described in the literature. In a forested wetland of

Fig. 4. Annual variation of the TP, PO_4^{3-}, NO_2^-, NO_3^-, and TSS retention efficiencies (±SD) in the South Lake Pátzcuaro wetland.

Louisiana, Blahnik and Day (2000) reported retention values of between 48% and 91%, and Knox *et al*. (2008) cited 77% in a natural California wetland. In constructed wetlands, reductions of 68% have been reported (Kadlec and Knight, 1996).

The nutrients retention in the Pátzcuaro wetland clearly shows its dependence on the hydrological cycle (Wetzel, 2001; Hakanson, 2004; AlMaarofi *et al*., 2013). P retention in wetlands is difficult to explain given the complex interactions taking place between hydrological and biogeochemical transformations, including assimilation by plants through photosynthesis (Hoffman *et al*., 2009; González-Alcaraz *et al*., 2012). For TP and PO_4^{3-}, the highest retention values were recorded during the dry period (Fig. 4). During this dry period, the residence time of low inflow water increased, which facilitates P retention by soil, this being one of the main mechanism involved in PO_4^{3-} retention in wetlands (González-Alcaraz *et al.*, 2012; Hoffman *et al*., 2012). Moreover, in the range of pH levels measured in the Pátzcuaro wetland (Tab. 2), dissolved phosphorus can precipitate as insoluble Ca or

Mg phosphates, or adsorbed as carbonates (Alvarez-Rogel *et al*., 2006). Additionally, P retention is related with uptake by emerging dense macrophyte communities that cover the wetland (Gagnon *et al*., 2012). Gómez *et al*. (2001) found that *Phragmites australis* was highly effective in the remove of phosphorus from the water in an artificial wetland, although high densities not improve nutrient retention. Besides the translocation of nutrients from shoots and leaves to roots during autumn reported by Meuleman *et al*. (2002) in *P. australis*, indicate that the response of the aquatic vegetation in a wetland may be influence by season of the year (Alvarez-Rogel *et al*., 2006). Both TP and PO_4^{3-} retentions also depend indirectly on organic matter (Bruland and Richardson, 2006). In fact during the dry period, we found negative and significantly correlations between %R of TP and BOD_5 input (Tab. 4).

During the rainy period, the Pátzcuaro wetland exports TP and PO_4^{3-} (Fig. 4), when the highest inflow concentrations are found (Tab. 2) and high inflow water and low residence time of water occurs. In a wetland of southern Spain was reported that during rainy periods, the effec-

Tab. 3. Total retention efficiency (%) during the rainy and the dry periods, and net retention and export for the nutrients and TSS recorded in the South Lake Pátzcuaro wetland.

	Total n=72		Rainy period n=30		Dry period n=42		Net retention		Export	
	R (%)	SD	R (%)	SD	R (%)	SD	R (%)	SD	R (%)	SD
TP (µg L^{-1})	30.35	38.82	-4.59	23.43	55.32	26.27	47.12 (n=54)	28.01	-19.93 (n=18)	16.72
PO_4^{3-}(µg L^{-1})	19.19	43.37	-20.18	27.63	47.32	27.79	43.87 (n=48)	27.60	-30.16 (n=24)	20.91
NO_2^- (mg L^{-1})	2.45	50.83	14.14	54.02	-5.90	47.32	40.97 (n=41)	20.82	-48.50 (n=31)	28.76
NO_3^- (mg L^{-1})	17.56	54.15	48.99	18.88	-4.88	59.88	38.76 (n=60)	27.14	-88.41 (n=12)	16.47
TSS (mg L^{-1})	14.68	40.70	44.52	18.96	-6.63	38.69	34.03 (n=52)	23.16	-39.29(n=20)	28.40

Tab. 4. Spearman correlation coefficients for the retention efficiency of the nutrients and environmental factors measured during the study period at the South Lake Pátzcuaro wetland.

	Rainy period (n=30)					Dry period (n=42)				
	TP %R	PO_4^{3-} %R	NO_2^- %R	NO_3^- %R	TSS %R	TP %R	PO_4^{3-} %R	NO_2^- %R	NO_3^- %R	TSS %R
Water temperature (°C)								-0.424**		-0.403**
pH		-0.543**						-0.429**		
Conductivity (µS cm^{-1})	-0.553**	-0.734**			-0.421*				-0.502**	0.306*
DO (mg $O_2 L^{-1}$)		0.409*						0.460**		
Input TP (µg L^{-1})	0.752**		-0.414*			0.531**	0.325*			
Input PO_4^{3-}(µg L^{-1})			0.377*	-0.390*						
Input NO_2^- (mg L^{-1})		0.438*	0.722**					0.368*	0.466**	-0.385*
Input NO_3^- (25mg L^{-1})									0.722**	-0.393**
Input BOD_5(mg $O_2 L^{-1}$)	-0.379*					-0.330*				
Input COD (mg $O_2 L^{-1}$)				-0.395*						
Input TSS (mg L^{-1})	0.502**							-0.407**	-0.636**	

*P<0.05; **P<0.01.

tiveness to reduce P concentrations diminishes (Álvarez-Rogel *et al*., 2006). The rainy period at Pátzcuaro occurs in summer months when the highest temperatures are recorded and coincide with the senescence of wetland plants (Raisin and Mitchell, 1995). Hence both the high inflow P concentration from runoff due to the anthropogenic activities (mainly organic effluents and diffuse source from agriculture) and plant biomass accrual can reduce a wetland's capacity to process P. In fact we found positive and significant correlations between %R of TP and both the input concentrations of TP and TSS (Tab. 4).

The seasonal pattern observed for nitrogen retention in the Pátzcuaro wetland is the opposite to P retention (Fig. 4). We found the highest retention values for both NO_2^- and NO_3^- during the rainy period. This pattern is unlike that which occurs in temperate environments (Fisher and Acreman, 2004), where the highest nutrient retention occurs in autumn to coincide with periods of increased precipitation and flow. The main NO_3^- retention processes are denitrification, plant uptake and microbial immobilisation (Reddy and Patrick, 1984; Groffman *et al*., 1992), whereas mineralisation of organic matter and its subsequent nitrification can result in the release of NO_3^- (Schade *et al*., 2002). Several authors have reported that denitrification can be especially important in aquatic ecosystems where fine sediments, high NO_3^- concentration, organic carbon availability, low redox potential and high water temperature exist (Inwood *et al*., 2007; Pinay *et al*., 2007). During the rainy period, we found that highest inflow NO_3^- concentrations and water temperatures were at their highest. Despite us not finding a correlation between water temperature and %R NO_3^-, the high values of NO_3^- inflow concentration recorded throughout the year suggest that denitrification may be the main removal process of nitrogen in the Pátzcuaro wetland. Denitrification can increase when flow rates through wetland is low and residence time is high (Garcia-Garcia *et al*., 2009), which occur in the Pátzcuaro wetland. In fact, except for two months at the end of the dry period (April and May), the Pátzcuaro wetland actively retained NO_3^- (Fig. 4). Seasonal NO_2^- retention dynamics is more difficult to explain. During the dry period, significantly and positive correlations were found between %R NO_2^- and DO and NO_2^- inflow concentration, which suggest that nitrification, determined by oxygen availability, may be the dominant process that increases NO_3^- concentration. Indeed a positive and significant correlation was found between %R NO_3^- and NO_2^- concentration input during this period. Typically, wetlands have been associated with reduced N loading rather than functioning to reduce P loading (Richardson, 1985; Fisher and Acreman, 2004). However, our results indicate that the Pátzcuaro wetland is more efficient at removing P than N, perhaps because significant amounts of P are stored by sedimentation (Johnston,

1991) and retained by clay particles (Craft and Casey, 2000). The TSS input into the Pátzcuaro wetland reached its maximum during the rainy period (mean TSS= 493.7 mg L^{-1}; Tab. 2), when the massive influx of sediment from the drainage basin of the wetland takes place (Jørgensen, 2003; Beltran-Vargas and Rangel-Ch., 2012) and re-suspension of sediments occurs. However, we also detected maximum retention during this period (44.52%; Tab. 3), probably because of the retention effect of emerging dense macrophyte communities that cover the wetland, as shown in other studies at similar latitudes (Abernethy, 1980). During the dry period, when the water flow speed slowed down and the water residence time was prolonged, TSS input lowered (Ockenden *et al*., 2012). TSS retention in the Pátzcuaro wetland is a response to both low-speed hydraulics, which results in a laminar flow, and resistance offered by roots and floating plants.

CONCLUSIONS

According to the data reported by different authors, the Pátzcuaro Lake has undergone very marked environmental degradation in the last 50 years (García-Villanueva, 2007; Bravo-Inclán *et al*., 2012).

Among the various causes, we find that diffuse pollution from agricultural areas is one of the most important impacts (Mijangos-Carros *et al*., 2008). One of the most relevant services provided by natural wetlands is their innate self-purification capacity. Hence the conservation and restoration of the Pazcuaro wetland are an excellent opportunity to make the best of its ability as a natural filter of the runoff water that the Pátzcuaro Lake receives. Despite Pátzcuaro wetland having been submitted to alterations, its ability to control nutrients has not become worse, as this study shows.

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