Journal of Coastal Conservation (2019) 23:445–460
https://doi.org/10.1007/s11852-018-0674-1

Management and restoration of dune lakes in Veracruz, Gulf of Mexico

Luis A. Peralta-Peláez[1] · Patricia Moreno-Casasola[2] · Iris Neri-Flores[2]

Received: 26 November 2017 / Revised: 24 November 2018 / Accepted: 6 December 2018 / Published online: 4 January 2019

Abstract

Dune lakes are formed in coastal dune depressions. A group of dune lakes in the state of Veracruz, Mexico, was decreed a Ramsar site and/or a state natural reserve. The objective of this study was to characterize and determine a baseline for these water bodies, both urban and rural, comparing them and establishing the guidelines for their management. The study points out the different threats and actual conditions of rural and urban dunelakes and the need for specific management practices. Our hypothesis stated that human activities around these lakes have an important impact and modify water quality, and that contact with the water table acts as a passive means of restoration. The water of 25 lakes was sampled to determine its quality, and wetland vegetation cover was monitored over time. Water quality was the main difference between urban and rural dune lakes; the latter, surrounded by cattle ranching activities and plantations, have lower concentrations of nitrates, ammonium, orthophosphates and total phosphorus. For management purposes, the lakes were divided into three groups (with subgroups) depending on their water quality, whether they are urban or rural, their size, whether or not they form part of the Ramsar site and/or natural reserve, or lie within the range of expansion of the Port of Veracruz. The management recommendations made for each lake are based on generating and applying current regulations, the enforcement of the law, carrying out infrastructure work, conservation and restoration actions, environmental education, organization and training. These lakes are important natural capital for the city, but management plans and ample participation by society are urgently needed.

Keywords Coastal dunes · Ecosystem services · Protected areas · Ramsar wetland · Rural wetlands · Urban wetlands

Introduction

Sand dunes are important ecosystems that are recognized for the coastal protection they provide during storms, hurricanes and storm surges (Spalding et al. 2014). In dune depressions, wetlands and even dune lakes can form part of these systems, increasing the ecosystem services they provide. Mexico has extensive coastlines bordered by beaches, sand dunes and coastal plains with freshwater wetlands. Coastal dunes are important ecosystems in Mexico and occupy an area similar to that of mangroves. The state of Veracruz, on the Gulf of Mexico, has one of the most extensive dune systems in the country (Martínez et al. 2014).

The Port and city of Veracruz, which merge with the city of Boca del Río, represent one of the country's most important economic centers, with a population of 752,111 people. The cities have grown over the floodplain of the Jamapa River, an area once covered by dunes and wetlands, replacing these ecosystems with urban development. The floodplain is an area of high marine and terrestrial biodiversity and floods are frequent. The federal government has created a protected natural reef area (Sistema Arrecifal Veracruzano), the state government has decreed a natural protected area with mangroves (Manglar de Arroyo Moreno), one with freshwater marshes (Tembladeras), and one with dune lakes and freshwater wetlands (a state reserve called Lagunas Interdunarias de Veracruz and Ramsar site 1450 MEX-055). Currently, these protected areas help conserve not only biodiversity, but also the ecosystem services that the wetlands provide. The government has recognized the role of these wetlands as regulatory vessels that help with flood containment (CONAGUA 2015; Gaceta Oficial de Veracruz CXCIV 2016), but in spite of the importance of these protected freshwater wetlands, at the moment there is no management plan.

✉ Luis A. Peralta-Peláez
peralta@itver.edu.mx

[1] Tecnológico Nacional de México/IT de Veracruz, Unidad de Investigación y Desarrollo de Alimentos (UNIDA). Lab. Ing. Ecológica Ambiental y Ciencias, Av. Miguel Angel de Quevedo 2779, Colonia Formando Hogar, 91860 Veracruz, México

[2] Instituto de Ecología, A.C., Red de Ecología Funcional, Carretera antigua a Coatepec 351, El Haya, Xalapa, 91070 Veracruz, México

In the depressions of coastal dune systems, humid areas can be found where humidity and flooding are variable. These areas are classified as: a) humid slacks (sensu Ranwell 1972) that form when the soil becomes saturated with water because of the proximity of the water table, and which are ephemeral, b) wet slacks that remain flooded for a period of time ranging from a few weeks to about 3 months, with flood tolerant species (Martínez et al. 1997), and c) dune lakes that are permanently flooded, or exist for more than 6 months of the year (Grootjans et al. 1998; Leentvaar 1997; Peralta-Peláez 2007; Peralta-Peláez and Moreno-Casasola 2009; Peralta-Peláez et al. 2014). In these water bodies, especially at their edges and in the shallower zones, there are wetlands (freshwater marshes with macrophytes and swamps) and some have extensive areas covered with floating vegetation. In years with severe drought, the volume of water can decrease significantly in some of the shallower lakes, which might even dry up for a few weeks (Leentvaar 1997; Peralta-Peláez 2007).

In Mexico, most of the dune lakes are located on the coastal plain of the state of Veracruz, though some are found in Tabasco and Oaxaca (Martínez et al. 2014). These lakes are formed mainly between the arms of the parabolic dunes and transgressive dunes. These ecosystems are not common because their formation requires a high water table from which sand can be blown by the wind to uncover humid sand, and that the sand stabilize enough so that it does not cover the exposed wet sand. Of the total national water that flows into the Gulf of Mexico, 25% circulates through the state of Veracruz (CONAGUA 2015), resulting in a superficial water table in coastal areas (Neri-Flores et al. 2014).

The fact that the dune lakes are localized and restricted to a specific region of our country along with the urban location of some of them have led to these lakes being considered very special ecosystems, unique in Mexico (Peralta-Peláez et al. 2014). Their value has been formally recognized under the Ramsar convention and since 2005, 11 lakes have been assigned to the Lagunas Interdunarias del Puerto de Veracruz Ramsar site (no. 1450) and the La Mancha dune lake is in the La Mancha-El Llano Ramsar site (no. 1336). In 2016 the state of Veracruz decreed 33 of them (including the 11 forming the Ramsar site) a natural reserve (Gaceta Oficial de Veracruz CXCIV 2016), also including some of the rural lakes, covering an area of 944.26 ha (see Table 1). These systems provide a variety of ecosystem services ranging from the aesthetic, to nesting and resting sites for local and migratory birds, and as water reservoirs and water holes for cattle. In some of them fish have been introduced for fishing activities and to alleviate poverty (Gaceta Oficial de Veracruz CXCIV 2016; Moreno-Casasola and Infante Mata 2010). At present, the urban dune lakes also function as flood control vessels, because their natural character allows them to accumulate more water and be flooded throughout the year as the water table level fluctuates, while in other areas of the city engineering infrastructure has been built to draw water out of the city during floods.

Dune lakes vary in size, in the area occupied by the open water, in the structure and composition of their wetland vegetation, the types of water runoff they receive, and therefore the presence of organic and inorganic contaminants, as well as their degree of urbanization (Table 1). In some, aquatic processes dominate, while in others there is extensive wetland vegetation, but in almost all of them there is an area of surface water that is not covered by vegetation (Peralta-Peláez 2007; Peralta-Peláez and Moreno-Casasola 2009).

In Mexico, there have been few studies on dune lakes. Martínez et al. (1997) and Moreno-Casasola and Vazquez (1999) analyzed the impact that flooding had on the plant succession of the La Mancha dune lake and the association between vegetation dynamics and water table fluctuations. Sarabia (2004) focused mainly on the physicochemical water analysis of some dune lakes around the Port of Veracruz, and Siemens et al. (2006) analyzed the growth of the port and the relationship of dune lakes to society. Yetter (2004) calculated the water balance of the rural La Mancha dune lake and its associated wetlands. Peralta-Peláez et al. (2007) described insect species diversity, and developed an integrated biological index of 14 dune lakes located in the rural area, based on aquatic insects (Peralta-Peláez 2007). In rural areas, when there is livestock activity, flood tolerant grass species become part of these wetlands (Peralta-Peláez and Moreno-Casasola 2009). Peralta-Peláez et al. (2014) analyzed the physicochemical characteristics of the water bodies of the rural dune lakes.

The aim of the present study was to document the baseline characteristics of the dune lakes of Ramsar site # 1450 and half of the dune lakes in the natural reserve, in order to draw up guidelines for the conservation and restoration of both rural and urban lakes, and to ensure that they continue to provide ecosystem services. The first objective was to compare the physical and chemical characteristics of the water of 25 dune lakes, both rural and urban, in the context of the soil use around them. The second objective was to analyze if in these systems, contact with the water table improved water quality, meaning this characteristic would offer an alternative to passive restoration. The third objective was to evaluate the transformation of vegetation cover and the degree of urbanization that have occurred in these dune lakes from 2002 to 2015 to assess trends and future impacts. These results will be the baseline for monitoring these ecosystems and help determine management and restoration needs.

The working hypothesis is that the dune lakes located in urban or semi-urban areas will exhibit a greater degree of degradation in water quality (greater amounts of nutrients) than those found in rural areas, but less than the lake with the discharge of waste water from the treatment plant due to the interaction of the dune lakes with the water table. Likewise, it is expected that the water of the rural lakes will have higher concentrations of

Table 1 Characteristics of the dune lakes in the central region of the state of Veracruz: location, size, depth, water sources, degree of urbanization, presence of livestock, type of lake depending on the soil use and dominant vegetation

Name and abbreviation	Coordinates	Size (ha)	Depth (cm)	Type	Distance to the sea (km)	Water sources	Dominant vegetation 2004–2007	Dominant vegetation 2016	Presence of livestock	% urbanization (2002) / % urbanizatioin (2016)	Is part of a Ramsar site/ or a natural reserve
La Mancha (LM)	19°35′ 37.01" N, 96°22′ 52.74" W	1.5	150	rural	0.59	Ag	*Pistia stratiotes*, *Cladium jamaicense*, *Pachira aquatica*, *Annona glabra*	mantained	no	zero/ zero	yes (site 1336)/ no
Don Gilberto (DG)	19°27′45.11" N, 96°20′ 51.86" W	10	150	rural	4.08	Ag	*Cynodon dactylo*n, *Thalia geniculata*, *P. stratiotes*	hydrophyte cover has decreased	yes	zero/ zero	no/ no
Félix (Fel)	19°26′28.94" N, 96°20′ 52.21" W	8	120	rural	1.78	Ag	*C. dactylon, T. geniculata*	mantained	yes	zero/ zero	no/ no
Tolega (Tol)	19°25′28.74" N, 96°20′ 25.86" W	5	120	rural	2.03	Ag	*P. stratiotes, Mimosa pigra*	mantained	yes	zero/ zero	no/ no
Jagüey (Jag)	19°26′21.0" N, 96°20′ 16.62" W	6	100	rural	1.8	Ag	*C. dactylon, T. geniculata*	mantained	yes	zero/ zero	no/ no
Oj (Ojite)	19°25′38.91" N, 96°19′ 55.45" W	1	150	rural	0.94	Ag	*C. dactylon, Pontederia sagittata, P. stratiotes*	hydrophyte cover has decreased	yes	zero/ zero	no/ no
Catalana (Cat)	19°17′44.28" N, 96°17′ 27.51" W	20	200	rural	2.1	Ag	*Typha domingensis*, *P. sagittata*	mantained	yes	zero, but subdivided/ zero, subdivided	no/ no
Colorada (Col)	19°17′10" N, 96°16′30" W	15	650	rural	1.98	Ag	*T. domingensis*, *Nymphoides indica*	mantained	yes	zero/ zero	no/ yes
San Julián (SJ)	19°15′21" N, 96°15′ 41.57" W	120	250	rural	2.7	Ag, Do	*T. domingensis*	mantained	yes	10/ 50 with port infraestructure	no/ yes
La Palma (LP)	19°15′00.42" N, 96°15′ 18" W	2	200	rural	3.13	Ag	*T. domingensis*	mantained	yes	zero/ zero	no/ no
Minerva (Min)	19°14′56.54" N, 96°15′ 14.41" W	1	150	rural	3.23	Ag	*P. sagittata, T. domingensis*	mantained	yes	zero/ zero	no/ no
Zendejas Zen)	19°14′08.00" N, 96°14′ 33.40" W	2	250	rural	3.79	Ag, SW, Do	*T. domingensis, P. sagittata*, *Ceratophyllum demersum*, *Utricularia gibba*	hydrophyte cover has decreased	yes	zero/ 40 with port infraestructure	no/ no
Manguito (Man)	19°14′03.64" N, 96°14′ 13.30" W	2	200	rural	4.03	Ag, SW	*T. domingensis, P. sagittata, C. demersum, U. foliosa*	mantained	yes	zero/ zero, with roads and railroad for the port	no/ no
Abascal (Abs)	19°14′05.30" N, 96°14′ 09.84" W	2	200	rural	4.03	Ag, SW	*T. domingensis, P. sagittata, C. demersum, U. foliosa*	mantained	yes	zero/ zero, with roads and railroad for the port	no/ no
Las Conchas (Con)	19°11′04.66" N, 96°10′ 52.36" W	15	250	semi urban	6.08	Ag, SW	*T. domingensis, U. foliosa, U. gibba*	hydrophyte cover has decreased	no	30/ 60	yes/ yes
Tarimoya (Tari)	19°11′47.76" N, 96°10′ 46.2" W	13	70	semi urban	5.45	SW, Do	*Eichhornia crassipes*, *Salvinia* sp.	there is no vegetation *	no	45/ 80	yes/ yes

Table 1 (continued)

Name and abbreviation	Coordinates	Size (ha)	Depth (cm)	Type	Distance to the sea (km)	Water sources	Dominant vegetation 2004–2007	Dominant vegetation 2016	Presence of livestock	% urbanization (2002) / % urbanizatioin (2016)	Is part of a Ramsar site/ or a natural reserve
La Colorada (LaCol)	19°11′47.76” N, 96°10′ 46.2” W	2	200	semi urban	5.4	SW, Do	*P. stratiotes, E. crassipes*	there is no vegetation *	no	100/ 100	yes/ no
Laureles (Lau)	19°10′44.99” N, 96°10′ 37.44” W	1	120	semi urban	5.8	SW, Do	*Salvinia sp., Cyperus sp.*	there is no vegetation *	no	50/ 100	yes/ yes
Dos Caminos (DosCam)	19°10′34.7” N, 96°10′ 24.7” W	3	200	urban	5.9	SW, Do	*T. domingensis, Paspalum sp.*	there is no vegetation *	no	80/ 100	yes/ yes
Encanto (Encan)	19°10′04.13” N, 96°09′ 19.87” W	3	140	urban	5.8	SW, Do	*E. crassipes, T. domingensis, Paspalum sp.*	there is no vegetation *	no	90/ 100	yes/ yes
Ensueño (Ensu)	19°10′10.38” N, 96°09′ 01.98” W	5	150	urban	5.8	SW, Do	*E. crassipes, P. stratiotes, T. domingensis*	there is no vegetation *	no	90/ 100	yes/ yes
Ilusión (Ilu)	19°10′05.13” N, 96°09′ 01.00” W	2	200	urban	4.15	SW, Do	*T. domingensis, P. stratiotes, T. geniculata*	there is no vegetation *	no	100/ 100	yes/ yes
Caracol (Carac)	19°09′33.29” N, 96°08′ 52.94” W	11	140	urban	3.9	SW, Do	*E. crassipes, P. stratiotes*	there is no vegetation *	no	60/ 100	yes/ yes
Coyol (Coyol)	19°09′37.66” N, 96°08′ 46.3” W	10	175	urban	3.2	SW, Do	*T. domingensis, T. geniculata*	there is no vegetation *	no	100/ 100	yes/ yes
Lake D	19°09′31.9” N, 96°09′ 22.06” W	4	130	urban	4.3	Ag, SW and water treatment plant (45m3s-1)	*P. stratiotes, Xanthosoma robustum*	there is no vegetation *	yes	50/ 75	yes/ yes

For sources of water, in all cases inputs are from groundwater and rainwater (so they are not indicated). Other water sources are the presence of infrastructure that collects and leads storm runoff from the streets to the lakes (SW), clandestine and official domestic points of discharge are indicated (Do), as is agricultural runoff (Ag) phosphorus compounds due to runoff and seepage from agricultural activities, while the urban lakes will have more nitrogen compounds from urban discharges. Dune lakes in rural areas are expected to have more structured wetland vegetation and less loss of terrestrial vegetation cover within 500 m radius, while in urban and semi-urban dune lakes, floating species are expected to be more common, indicating pollution.

Methodology

Study area

The dune lakes we studied are located on the coastal plain of the central Gulf of Mexico (19°35′45.48” N, 96°22′52.76” W and 19°09′31.9” N, 96°09′22.06” W). Figure 1a shows the location of rural and urban dune lakes and a Google Earth image (Fig. 1b) shows the density of towns around them. They are located on the coastal part of the lower basins of the Actopan and Jamapa-Cotaxtla rivers. With regard to groundwater, the lakes belong to aquifer 3005 of the Actopan Valley (LM (La Mancha), DG (Don Gilberto), Fel (Félix), Tol (Tolega), Jag (Jagüey), Oj (Ojite)) and the rest to the aquifer 3006 Costera de Veracruz (DOF 2003).

The climate of the area is subhumid tropical with summer rains (Aw). Annual average rainfall is 1550 mm and average annual temperature is 26 °C (García 1987). The nomenclature used to identify the dune lakes is that used on official government maps (INEGI vegetation and land use maps). When no name had been registered, we used the dune lake’s local name.

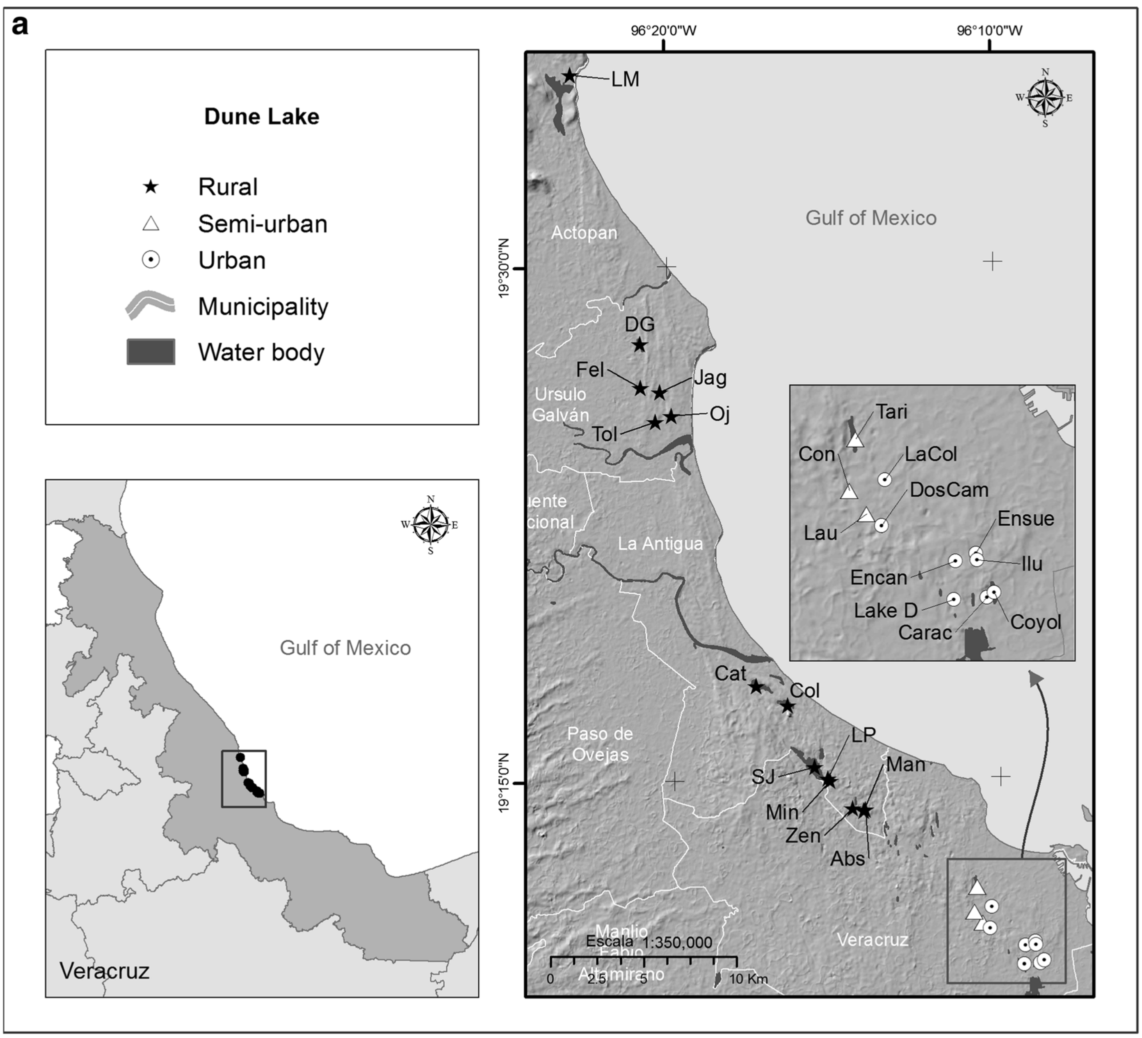

Fig. 1 **a** Location of interdunary lagoons in the central region of the state of Veracruz, Mexico. LM (La Mancha), DG (Don Gilberto), Fel (Felix), Tol (Tolega), Jag (Jagüey), Oj (Ojite), Cat (Catalana), Col (Colorada), SJ (San Julian), LP (La Palma), Min (Minerva), Zen (Zendejas), Man (Manguito), Abs (Abascal), Tari (Tarimoya), Con (Conchas), LaCol (La Colorada), Lau (Laureles), DosCam (Dos Caminos), Encan (Encanto), Ensue (Ensueño), Ilu, Carac, Coyol, Lake D. **b** Location of urban and semi-urban dune lakes in Veracruz, Mexico. Con (Conchas), Tari (Tarimoya), LaCol (La Colorada), Lau (Laureles), DosCam (Dos Caminos), Encan (Encanto), Ensue (Ensueño), Ilu (Ilusión), Carac (Caracol), Coyol, Lake D (Lake D). The image for the urban zone is from Google Earth, so that town densities can be appreciated

Fig. 1 continued.

When a lake had no name, we used the name of the owner of the ranch where it was located.

Delimitation of lakes, and changes in land use and vegetation

A 500 m radius was established around each lake from the central point of each body of water to analyze its surroundings. In urban areas, we used this area to calculate the degree of urbanization and/or the presence of patches of herbaceous or arboreal vegetation characteristic of coastal dunes. In rural lakes, land use and/or vegetation type was assessed. In both cases, the activities carried out within the 500 m radius and on the lake itself were recorded through field visits and in talks with the owners or users. For this same radius, the Landsat satellite images (Image © 2016 TerraMetrics, Data SIO, NOAA, US Navy, NGA, GEBCO, Image © Digital Globe) were analyzed using Google Earth images for 2002 to 2016 (Time Lapse application of Google Earth). On these images we marked the limits of the wetland vegetation of each lake in 2002 and in 2016 within the same perimeter.

Sampling and laboratory analysis

In all lakes, water samples were taken from the surface, at no more than 20 cm deep because some lakes were shallow (Table 1). This ensured that the sampling depth was constant. Samples were stored in ice at 4 °C, in new and washed plastic bottles, one liter capacity, and transported to the laboratory. Five transects were set up per lake, four parallel to the shore that formed a square, and another in the center. Fifteen samples were taken from each lake, three per transect. For urban lakes, data were taken from Sarabia (2004), who used the same methodology. In one of the lakes (Lake D, in Lomas del Coyol where there is a wastewater treatment plant), there were three more sampling points: one at the outlet of the wastewater discharge, another after the water had passed through the wetland dominated by *Xanthosoma robustum* Schott, and a third at the other end of the lake directly opposite the discharge.

The physicochemical parameters measured in situ were temperature, conductivity, salinity, pH and percent oxygen saturation using a YSI 6600 multiparametric device, with readings taken between 9 and noon. Also, at each sampling site the depth (approximate, due to the muddy soil) at the center of the lake was measured, using a rod marked in centimeters. The measurements of the groundwater levels took place every 2 weeks between March 2017 (March–May corresponds to the dry season) and September of 2017 (June–September corresponds to the wet season), using a piezometer in Lake Tarimoya (796,490.6 UTMx, 2,125,028.8 UTMy) with a depth of 1.20 m and located 150 m from the coastal line. Vegetation data were taken from Sarabia (2004) and Peralta-Peláez (2007), which correspond to 1 year of sampling, and later in 2015, when the overall floristic composition had changed.

Based on APHA-AWWA-WPCF (1990), the following laboratory analyses were performed: for nitrates, the Brucine colorimetric method; for ammonium, the Nessler method; for total phosphorus, the ascorbic acid method.

Data analysis

For each lake, the mean (based on all the transects in a lake) and standard deviation of each chemical and physical parameter were calculated. A nonparametric ANOVA (Kruskall-Wallis) was run for each of the variables to see if there were any differences among lakes. Multiple comparisons were made with the Tukey test (Legendre and Legendre 1998; Zar 1999) run in Statistica Ver. 8 (StatSoft Inc 2004). The ordination was done using the Principal Components Analysis (PCA) run in PC-ORD, Version 5 (Mc Cune and Grace 2002). We used the matrices with the mean value per parameter per lake for the following parameters: salinity, pH, percent oxygen saturation, ammonium (NH4-), nitrates (NO3-), total phosphorus and reactive phosphorus (PO4-). The variables used to represent human activity were presence (or absence) of livestock and, since there was no information on livestock load only the presence of pastures suitable for grazing livestock was noted, and the degree of urbanization as indicated by the percent of the area within the 500 m radius covered by infrastructure.

Results

The dune lakes studied vary in size from one hectare to 120 ha (Table 1). They are located in rural and urban areas, and on analyzing our results, we detected a third type: semi-urban lakes. These are located at the urban limit and with less than 50% urbanization in their 500 m perimeter. Of 25 dune lakes, seven were urban, four were semi-urban and 14 were rural (Fig. 1a). Over time, differences were found for a given lake in both the vegetation cover and the degree of urbanization. The Don Gilberto, Zendejas, Ojite and Las Conchas rural dune lakes, decreased in their vegetation cover of hydrophytes. The urban lake and the three semi-urban lakes in the Municipality of Veracruz were under a management program that indicates the removal of all vegetation every year (Table 1). In the La Mancha, Don Gilberto, Felix, Tolega, Jagüey, Ojite, Catalana, Colorada, La Palma and Minerva dune lakes, the surrounding area is still agricultural, with arboreal vegetation present within the 500 m perimeter. In the San Julián, Abascal, Zendejas and Manguito dune lakes, vegetation cover is maintained and there is agricultural activity, but from 2011 on we began to observe changes in the dune vegetation surrounding the lakes. These changes became more evident by 2016, when there was not only a loss of plant cover but also a change in the lake's surface hydrology resulting from the construction of hydraulic channels in the area as part of the construction of infrastructure for the expansion of the Port of Veracruz. For the Las Conchas, Tarimoya, Laureles, Caracol and Lake D dune lakes, the proportion of land used for urban purposes increased by 25% to 50% (Table 1). In urban lakes, growth was observed in the residential areas around the El Ensueño, Dos Caminos and Encanto dune lakes.

Water quality

The physicochemical parameters differed significantly between the lakes as a function of the type of land use in the vicinity of the lake (Table 2). The main differences between urban and rural lakes occur in water quality. Rural dune lakes have better water quality with lower concentrations of nitrates, ammonium, orthophosphates and total phosphorus. Lake D had the highest concentrations of ammonium, phosphates and total phosphorus, similar to the discharge of wastewater that enters this site from the treatment plant. Each of the environmental parameters is described below.

The salinity analysis shows that all the dune lakes are fresh water lakes (oligohaline), with salinity values ranging from 0.03 to 0.69 ppm, in spite of their proximity to the sea. There were significant differences among lakes (H (26, N = 170) = 139.55 $p < 0.001$), but all of them are fresh water lakes. pH was 6.2 to 9.2, with significant differences between some

Table 2 Mean values and standard deviation of the physicochemical parameters of the dune lakes in central Veracruz, Mexico

Dune lake	Temperature (°C)	Salinity (ups)	pH	% oxygen saturation	Ammonium mgL^{-1}	Nitrate mgL^{-1}	Orto-phosphates mgL^{-1}	Total phosphorous mgL^{-1}	Location
La Mancha (LM)	28.3 ± 1.0 a	0.24 ± 0.03a	7.7 ± 0.1a	40.4 ± 16.4a	0.37 ± 0.5a	3.8 ± 2.2c	0.05 ± 0.0a	0.18 ± 0.1a	rural
Don Gilberto (DG)	30.2 ± 4.1a	0.03 ± 0.01b	6.2 ± 0.3a	88.2 ± 57.3a	0.38 ± 0.3a	1.1 ± 0.7a	0.03 ± 0.0a	0.56 ± 0.4a	rural
Félix (Fel)	28.8 ± 1.0a	0.04 ± 0.0b	6.2 ± 0.4a	92.0 ± 23.1a	0.87 ± 0.8a	0.17 ± 0.1a	0.08 ± 0.1a	1.0 ± 0.1a	rural
Tolega (Tol)	19.6 ± 0.4 a	0.10 ± 0.01b	6.6 ± 0.2a	52.2 ± 15.6a	0.68 ± 0.7a	0.16 ± 0.2a	0.16 ± 0.0a	0.26 ± 0.1a	rural
Jagüey (Jag)	27.5 ± 1.7 a	0.08 ± 0.0b	6.4 ± 0.5a	75.7 ± 30.6a	0.67 ± 0.9a	0.19 ± 0.2a	0.24 ± 0.0a	0.35 ± 0.2a	rural
Oj (Ojite)	28.4 ± 2.8 a	0.25 ± 0.11a	7.0 ± 0.2a	42.7 ± 18.2a	0.50 ± 0.5a	0.52 ± 0.2a	0.08 ± 0.1a	0.66 ± 0.2a	rural
Catalana (Cat)	25.4 ± 3.4 a	0.20 ± 0.04a	8.0 ± 0.7a	137.7 ± 57.9a	0.50 ± 0.5a	0.52 ± 0.1a	0.02 ± 0.0a	0.33 ± 0.7a	rural
Colorada (Col)	29.7 ± 1.1b	0.22 ± 0.01a	8.7 ± 0.1b	107.4 ± 15.2a	0.43 ± 0.4a	0.30 ± 0.1a	0.01 ± 0.0a	0.36 ± 0.3a	rural
San Julián (SJ)	29.0 ± 1.5b	0.14 ± 0.02b	9.2 ± 0.4b	150.7 ± 22.1a	0.30 ± 0.2a	0.39 ± 0.1a	0.01 ± 0.0a	0.51 ± 0.4a	rural
La Palma (LP)	28.7 ± 3.1 a	0.37 ± 0.11a	7.2 ± 0.2a	51.4 ± 55.9a	0.45 ± 0.4a	0.39 ± 0.04a	0.02 ± 0.02a	0.40 ± 0.3a	rural
Minerva (Min)	24.8 ± 0.3 a	0.29 ± 0.03a	7.1 ± 0.1a	17.1 ± 4.4a	1.38 ± 0.2a	0.88a ± 0.1a	0.49 ± 0.3a	1.8 ± 0.6a	rural
Zendejas (Zen)	27.0 ± 2.2 a	0.23 ± 0.07a	7.1 ± 0.3a	21.9 ± 1.5a	0.25 ± 0.2a	0.30 ± 0.04a	0.01 ± 0.0a	0.39 ± 0.3a	rural
Manguito (Man)	23.4 ± 4.7 a	0.25 ± 0.02a	7.3 ± 0.2a	24.2 ± 2.0a	0.62 ± 0.6a	0.44 ± 0.2a	0.01 ± 0.0a	0.37 ± 0.3a	rural
Abascal (Abs)	24.9 ± 3.9 a	0.25 ± 0.04a	7.4 ± 0.1a	65.9 ± 2.1a	0.46 ± 0.4a	0.35 ± 0.04a	0.01 ± 0.0a	0.36 ± 0.3a	rural
Las Conchas (Con)	28.9 ± 2.7 a	0.25 ± 0.05a	7.4 ± 0.4a	69 ± 3.0a	0.23 ± 0.2a	0.74 ± 1.2a	0.02 ± 0.0a	0.43 ± 0.3a	semi-urban
Tarimoya (Tari)	22.9 ± 0.4 a	0.34 ± 0.1a	7.8 ± 0.1a	237.2 ± 32.3b	1.26 ± 0.1a	0.81 ± 0.1 a	0.86 ± 0.9 a	7.71 ± 0.9 b	semi-urban
Colorada (LaCol)	19.3 ± 0.1 c	0.45 ± 0.0 d	8.6 ± 0.1b	250 ± 0.0 b	0.51 ± 0.0a	36.87 ± 0e	2.17 ± 0.1ab	22.16 ± 15.3e	semi-urban
Laureles (Lau)	23.1 ± 0.3 a	0.21 ± 0.0 a	8.4 ± 0.2b	235.5 ± 31.3b	1.83 ± 0.3b	1.06 ± 0.2 b	5.81 ± 3.2 b	9.73 ± 6.8 b	semi-urban
Dos Caminos (DosCam)	23.8 ± 0.1 a	0.28 ± 0.0 a	9.2 ± 0.3bc	250 ± 0.0bc	1.44 ± 0.1 b	0.79 ± 0.0 a	1.19 ± 1.0ab	11.78 ± 0.7 b	urban
Encanto (Encan)	22.03 ± 0.1 a	0.17 ± 0.0 a	8.4 ± 0.2 b	235.33 ± 11.7b	1.35 ± 0.0 b	0.94 ± 0.0 a	3.42 ± 0.3 b	13.29 ± 1.1b	urban
Ensueño (Ensue)	21.3 ± 0.2 a	0.24 ± 0.0 a	9.2 ± 0.3bc	250 ± 0.0 b	0.37 ± 0,0 a	1.46 ± 0.1 b	2 ± 0.1 b	18.28 ± 0.6 b	urban
Ilusión (Ilu)	18.1 ± 0.3 a	0.38 ± 0.0 a	7.7 ± 0.1 a	217.33 ± 32.0b	0.17 ± 0.0a	1.05 ± 0.1 b	0.97 ± 0.3ab	10.17 ± 2.2 b	urban
Caracol (Carac)	20.1 ± 0.3 a	0.69 ± 0.0 c	7.8 ± 0.1a	229.83 ± 23.3b	0.21 ± 0.0 a	1.34 ± 0.0 b	1.18 ± 0.2 ab	13.17 ± 1.3 b	urban
Coyol (Coyol)	21.8 ± 0.1 a	0.27 ± 0.0 a	8.2 ± 0.1 a	169.66 ± 25.1b	1.43 ± 0.0b	8.44 ± 0.4 d	0.01 ± 0.0 a	11.30 ± 0.5 d	urban
Lake D	21.91 ± 1.91 a	0.29 ± 0.2 a	7.5 ± 0.35 a	60.18 ± 38.39 a	3.17 ± 3.17 c	3.0 ± 4.15 c	0.004 ± 0.00 a	3.40 ± 0.25 c	urban
Lake D-Dis	24.3 ± 0.1 a	0.4 ± 0.00 a	7 ± 0.00 a	31.1 ± 2.72 a	4.88 ± 0.21 c	11.2 ± 0.52 d	0.004 ± 0.003a	5.09 ± 0.08 c	urban
Lake D- Wet	24.17 ± 0.93 a	0.33 ± 0.06 a	7 ± 0.00 a	46.7 ± 22.03 a	3.52 ± 1.12 c	4.87 ± 3.58 c	0.006 ± 0.007 a	4.06 ± 0.69 c	urban

Dune lake names are from official maps (INEGI vegetation and soil use), or are the local names or the name of the owner of the land. Significant differences between means are given based on Kruskal-Wallis Anova analysis of one H-path (27, $N = 174$) by ranges. Multiple comparisons by ranges for all groups, $p > 0.001$

urban, semi-urban and rural lakes (H (26, $N = 170$) = 134.6 $p < 0.001$) (Table 2). The same was observed for percent oxygen saturation (H (26, $N = 170$) = 130.3 $p < 0.001$). Values above 200% saturation were recorded in the urban area (Tarimoya, La Colorada, Laureles, Dos Caminos, Encanto, Ensueño, Ilusión and Caracol), and the lowest values (17% and 21%), in the rural area.

The greatest differences in nutrient concentrations were detected between urban and rural lakes. This is due to the wastewater discharges from the treatment plants as well as from the untreated (clandestine) water drains in urban areas and the waters that drain from the agricultural fields (sugarcane crops). Of the nitrogen compounds, ammonium varied from 0.17 to 4.88 mgL^{-1}, with differences mainly observed between urban lakes (Laureles, Dos Caminos, Encanto, Coyol, and Lake D), which had higher concentrations (H (28, $N = 169$) = 101.5 $p <= 0.001$), and rural dune lakes. The highest values were recorded at the point of discharge of the treatment plant in Lake D. The same trend was found for nitrates (Table 2). In the group of rural lakes, Don Gilberto and La Mancha (1.1 and 3.8 mgL^{-1} respectively) had values similar to those found for most urban lakes. Within the group of urban and semi-urban lakes, nitrate concentration ranged from 0.39 to 36.87 mgL^{-1} (H (26, $N = 169$) = 134.2 $p < 0.001$), with the highest values recorded for Lake D, Coyol, and especially in La Colorada.

Orthophosphate was similar between the rural lakes, ranging from 0.01 to 0.24 mgL^{-1}, except for Minerva which had a somewhat higher value (0.49 mgL^{-1}). There were significant differences (H (26, $N = 169$) = 132.9 $p < 0.001$) between rural and urban and semi-urban lakes. The lowest values of all were recorded in Lake D. Total phosphorus was between 0.16 to 22.16 mgL^{-1} and had the same pattern as orthophosphate (H (26, $N = 169$) = 134.6 $p < 0.001$) (Table 2). La Colorada had the highest values, as it did for nitrates.

The Principal Components Analysis (PCA) indicates that the first two axes account for 67.04% of the variation. The variation on I axis is given by pH ($r = -0.77$), percent oxygen saturation ($r = -0.89$), total phosphorus ($r = -0.94$), orthophosphates ($r = -0.72$), and a gradient of higher to lower nitrate concentration ($r = 0.57$). The rural dune lakes are clearly separated (to the right of the ordination space including the semi-urban dune lake and Lake D) from the urban dune lakes (on the left), forming two groups. The variation on axis II is explained by ammonium ($r = 0.84$) (Fig. 2). The most eutrophic rural lakes are located at the top of axis II, and are the ones with livestock activities and sugar cane plantations. The rural lakes with better water quality are located on the lower right, along with the semi-urban lakes. At the top of the graph is the discharge point of waste water (Lake D), followed by the wetland of Lake D and then the lake itself, showing the wetland's capacity to purify the water. San Julian is at the other extreme of the gradient (Table 2), at the bottom of the graph, with lower ammonium concentration.

Groundwater fluctuation

Groundwater level remains at a lower depth, 1.2 m, from March to mid May, when it starts to rise. July, when the rainy season begins, the level of the groundwater is getting closer to the surface. By September there was an increase of almost 15 cm (Fig. 3).

Discussion

From this analysis we conclude that the dune lakes studied are shallow fresh water lakes (except La Colorada), most of which are permanently flooded, with the exception of four lakes that are dry for about 2 months during the dry season. The lakes have a neutral to slightly basic pH, with predominantly herbaceous wetland vegetation that is distributed mainly around the periphery. The activities carried out around these lakes increase the nutrient content of their water, as do the poor management practices used.

Based on the satellite image analysis we observed that lakes in the rural area are under pressure from agricultural activities. Others, due to their proximity to the Port of Veracruz, are now affected by construction associated with the expansion of the port. This indicates that the port expansion has increased the degree of urbanization of these lakes, because of their closeness to the city. The hydraulic infrastructure of the port and the growth of the cities of Veracruz and Boca del Río have not taken into account the need to maintain the water quality of these ecosystems. Nowadays, these dune lakes serve as both clandestine and authorized urban drainage areas, as well as drainage points for storm water, which also carries pollutants. This indicates that increasing urbanization, the way it is currently managed, will lead to further deterioration.

The lakes generally had neutral pH values (pH =7 ± 1). pH likely remains relatively stable in this type of water body owing to the buffering capacity of the carbonates. Only in the La Mancha dune lake has stratigraphy been documented in the work of Primeau (2004), who found a calcareous stratum whose origin was the shells of small marine organisms, and reported total alkalinity of 287 to 459 mgL-1 (corroborated by Peralta-Peláez 2007; Peralta-Peláez et al. 2014) and a pH of 7. For this same lake, Yetter (2004) mentioned that the pH (6.2–7.9) increased as the depth of the water table increased and that alkalinity was highly variable in the area with values ranging from 100 mgL^{-1} to >500 mgL^{-1}. The existence of a calcareous stratum may explain the high alkalinity

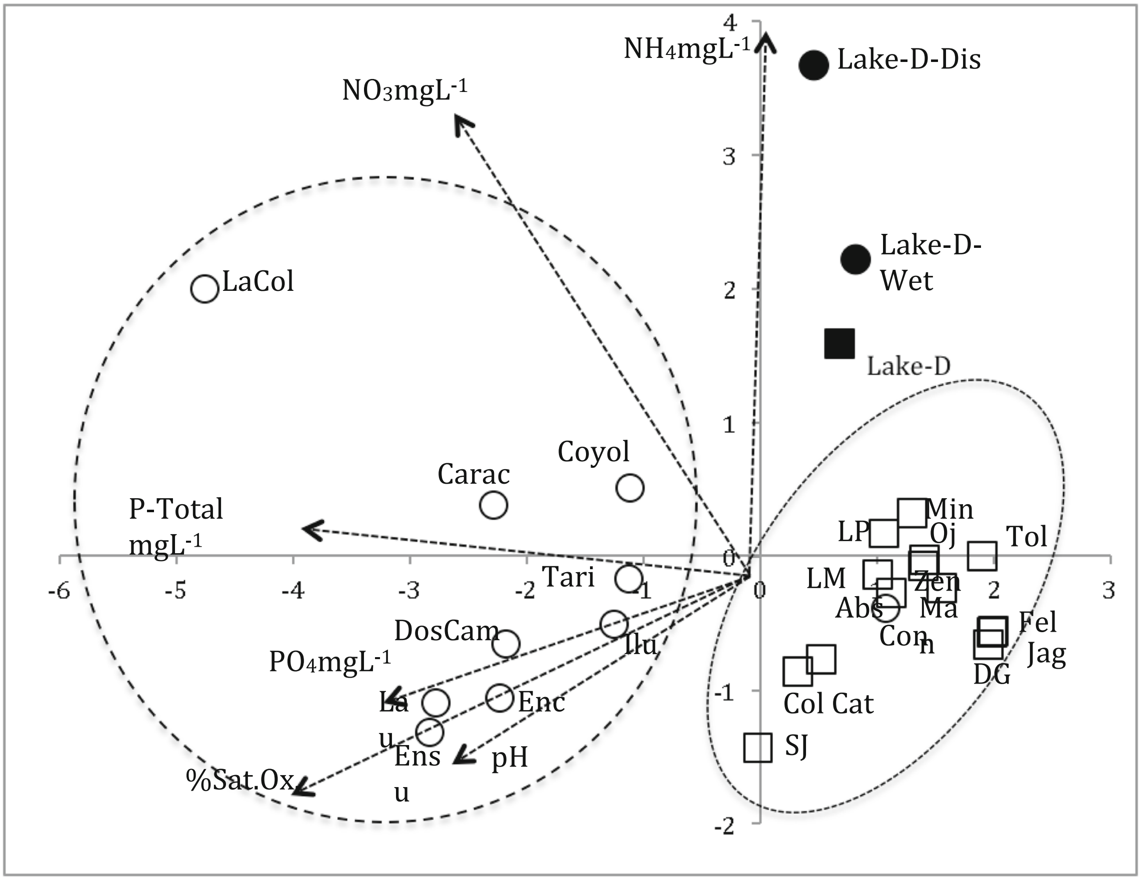

Fig. 2 Ordination analysis (PCA) showing the first two axes, which explain 67.04% of the variation. Along axis I there is a gradient (left-right) from urban lagoons to semi-urban and rural, with contaminants changing with lakes eutrophicated by phosphorus and nitrogen compounds (all urban or semi-urban) at one end, and the rural lakes with high agricultural activity and relatively high ammonium concentrations at the other. On Axis II a higher degree of contamination is observed in the lagoons in the upper part of the graph, mainly by nitrogen compounds, and this decreases towards the lower part. Open circles indicate urban lagoons, open squares are rural lagoons and the closed circle is the waste water discharge point (Lake D-Dis) and the sampling in the *Xanthosoma* wetland, once water had passed through the vegetation, Lake D-Wet). The closed square is the sampling point furthest from wastewater discharge on Lake D

concentrations measured as carbonates. Carbonates may regulate pH in these lakes. Jagüey, Felix, Tolega and Don Gilberto lakes (all rural) had pH <6.5 and all of them dry up during the dry season with only the lakebed remaining damp. This leads to a change in water pH when organic matter decomposes at the beginning of the rains (Wetzel 1981).

All of the lakes had an excess of nutrients. The first source of nutrients in all lakes is the organic matter produced by the accumulation of plant litter from the lakes' wetland vegetation. This is a function inherent to wetlands that allows them to accumulate organic matter, which later leads because of anaerobic conditions, to low decomposition rates and organic carbon accumulation (Hernández 2010). The second most important nutrient input pathway for the rural lakes is the leaching of fertilizers used on sugar cane crops and livestock pastures, as occurs around the Don Gilberto, Ojite, Felix, Jagüey and Tolega lakes (Fig. 2) (Peralta-Peláez 2007; Peralta-Peláez et al. 2014). Urban (except Lake D) and semi-urban lakes receive additional nutrients directly from untreated domestic discharge (both clandestine and authorized), and from storm water runoff that is channeled to the lakes (Table 1. Sarabia 2004; Siemens et al. 2006). The lakes with higher concentrations (> 1 mgL^{-1}) of ammonium, nitrates, orthophosphates and total phosphorus are mainly urban and semi-urban (Fig. 2, Table 2). The concentration of phosphorus compounds in these water bodies fall within the ranges proposed by De la Lanza (1996), Fukuhara et al. (2003), and Hoz and De la Lanza (2000) for eutrophic lakes and lagoons (Table 3). For this same parameter, based on the Official Mexican Standard (NOM-001-SEMARNAT-1996), in most cases the concentration of total phosphorus is above the value established for natural and artificial reservoirs (5 mgL^{-1}, for urban public use). However, the values recorded for all the lakes are lower than those of the waste water discharge into Lake D, where the treatment plant is located. We think this results from the contribution of groundwater, the level of which is very high on the coastal plain of Veracruz (Neri-Flores et al. 2014) and could be diluting and transporting

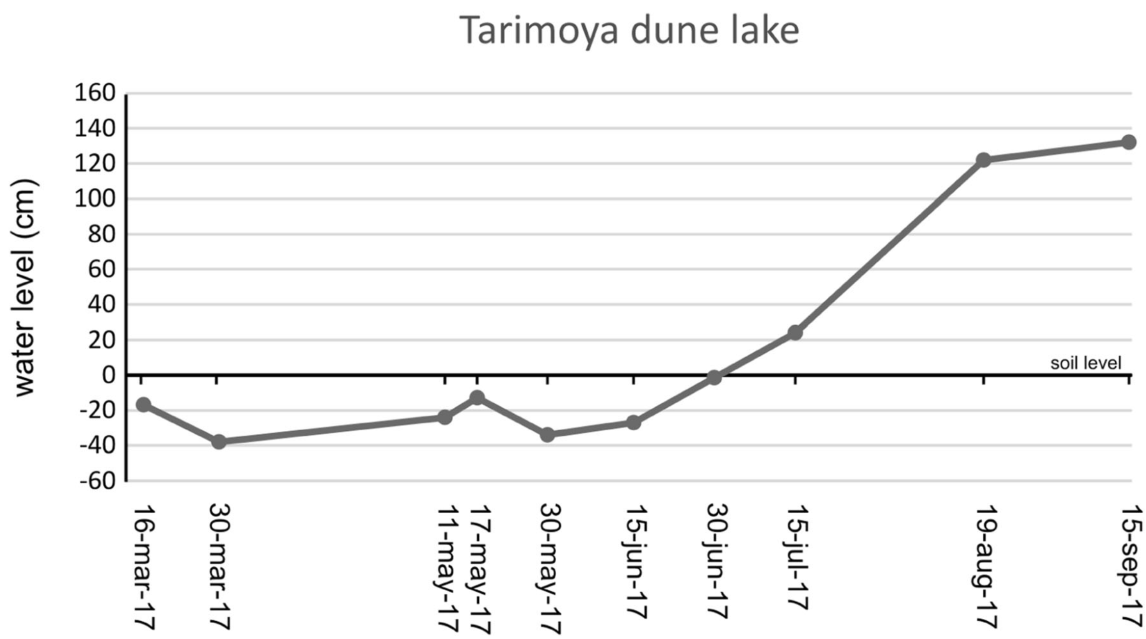

Fig. 3 Groundwater level fluctuation in a piezometer in Tarimoya dunelake showing an increase in the level with the rainy season

excess nutrients. During the rainy season, groundwater level rises (Fig. 3) and contributes to pollutant dilution.

The concentrations (<1 mgL^{-1}) of nitrogen (ammonium and nitrate) and phosphorus compounds (orthophosphates and total phosphorus) were significantly different among urban and rural lakes and the semi-urban Las Conchas dune lake (Fig. 2). The latter is located on the periphery of the port, but the dunes that surround it are being illegally settled by poor families who build their homes there. For most of the rural lakes, concentrations are below those reported by Fukuhara et al. (2003) and Vázquez (2004) (Table 3). The abundance of aquatic vegetation in the lakes helps to purify water (King et al. 2004; Whigham et al. 1988) and may also be helping to reduce nutrient concentrations in these dune lakes. The

Table 3 Comparison of physicochemical values of water in different lakes and lagoons around the world and in Mexico

Parameter	a	b	1	2	3	4	5	6	7	8
Depth	---	---	1–1.5	---	---	---	---	7.02	12.85	---
Temperature (°C)	<15–32	>20–32	8.9–30	---	---	---	---	16–24	24–27	26.3
Conductivity (mS/cm)	---	---	---	500	300	---	57?	---	---	---
Salinity (ups)	0.1–10	0–80	---	---	---	---	---	---	---	---
pH	6.5–9.0	6.5–9.0	6–10.0	8	8.0–8.5		4	7.5–8.5	7.5–8.5	6.8
Dissolved oxygen (mgL^{-1})	3.0 - >5.0	2.0–8.0	---	---	---	---	---	27–23	14–16	2.9
% oxygen saturation	---	---	20–140?	---	---	---	---	149	100	---
ORP (mV)	---	---	---	---	---	---	---	---	---	---
Alcalinity (mgL^{-1} of CaCO3)	15–20	>120	---	---	---	---	---	50–150	50–150	---
Ammonium (mgL^{-1})	ID - 0.5	ID - 0.5	0.3–0.8	0.15–1.1	0.5	---	---	---		---
Nitrates (mgL^{-1})	ID - 1.0	ID - 1.0	9.3–17.75	< 0.03	<0.03	10.0–15.0	0.008	---	---	---
Nitrites (mgL^{-1})	ID - 0.05	ID - < 0.05	---	---	---	---	---	---	---	---
Phosphorous orthophosphates (mgL^{-1})	ID - <0.5	ID - < 0.2	0.033–2.88	<0.03	<0.03	0.1–0.2	0.11	---	---	---
Total phosphorous (mgL^{-1})	---	---	---	---	---	---	---	---	---	<0.1
Cl^{-} (mgL^{-1})	---	---	---	100	40–50	30–100	1.5	---	---	---

The value interval of the basic parameters of lakes and reservoirs (column a) and for lagoons and estuaries (column b) reported by (De la Lanza 1996), (1) Intertidal Lake Sagate, Japan (Fukuhara et al. 2003); (2) Breefe Water, dune lake in Germany; (3) dune lake in Oered, Germany; (4) average values of German dune lakes (Leentvaar 1997); (5) Lake Michigan wetlands (Whigham and Jordan 2003); (6) and (7) tectonic-volcanic lagoons in the Mexican tropics (Torres-Orozco et al. 1994); (8) jagüey (waterhole) in a shallow lake, Mexico (Hoz and De la Lanza 2000); ID = undetectable value; (—) indicates that the data is not available or the units reported are different from those used in this study wetland vegetation of the dune lakes includes species that are often used in artificial wetlands for water treatment, e.g. *Typha domingensis* Pers. and *Pontederia sagittata* C. Presl. It can be concluded that the lakes that preserve wetland vegetation favor the biogeochemical processes that translate into the ecosystem services of water purification and contaminant immobilization. Urban lakes have free-floating hydrophytes that also help clean water (Table 1) but the authorities remove them every year.

This creates a gradient (Fig. 2, Table 2) with lakes eutrophicated by phosphorus and nitrogen compounds (La Colorada, Caracol, Ilusion, Ensueño, Dos Caminos, Laureles, Coyol, Encanto, and Tarimoya - all urban or semi-urban) at one end, and the rural lakes with high agricultural activity and relatively high ammonium concentrations at the other. In between are the lakes that have been less affected, mostly rural (La Mancha, Zendejas, Catalana, Colorada, La Palma, Abascal, Manguito) with two semi-urban lakes (Conchas and San Julián). Thus, our hypothesis can be accepted: the degree of pollution of rural and urban dune lakes depends on their location, being highest in urban settings and lower in rural settings, and thus on the way the surrounding soil is used and the management practices to which it is subjected.

There are still many unanswered questions regarding the hydrology of these lakes. Rhymes et al. (2014) concluded that dune slacks in North Wales experience considerable within-year and between-year variation in the water table and that there is a considerable influence of groundwater nutrients on water chemistry, soil chemistry and dune slack vegetation composition. Curreli et al. (2013) indicate that dune slacks are a seasonal coastal wetland habitat, whose plant assemblages and soil properties are strongly linked to a fluctuating water table. Yetter (2004), in a study on the dynamics of the water table in the La Mancha dune lake, found that 75% of the water in these wetlands is from the water table, coming from two sources, one distal (Sierra de Manuel Díaz) and the other proximal (the local dune system). The permanent orientation of the flow is from north to south, from the herbaceous wetland and dune lake, towards the mangrove and the La Mancha coastal lagoon, with a hydraulic conductivity of 2–10 cm/s. Unfortunately, this type of information only exists for this dune lake. There are no data on the extent or flow of the water table for the rest of the region, though there is nothing to suggest that the behavior is different elsewhere or that there are other inputs of water more important than that of groundwater. This is indirectly corroborated by the behavior of the contaminants in Lake D, which receives the sewage from treated water. In this 4.3 ha lake, ammonium and orthophosphate concentrations decrease from one extreme of the water body to the other, indicating that the lake has a certain capacity to purify the wastewater it receives. Neri-Flores et al. (2014), working north of the Port of Veracruz in the municipality of Jamapa, also mention that the water table is extremely superficial and when it rises during the rains, it is responsible for many of the floods. Our piezometer data showed an increase in groundwater levels during the rainy season. This indicates a saturation of soil pores, which do not allow more water infiltration, except for the one slowly flowing out. Therefore, from the direct evidence of the work of Yetter (2004) and piezometer data and the other two indirect pieces of evidence, it is possible to propose as a hypothesis for future studies that an important source of water for these lakes is the water table. While further studies are needed to determine the role of the water table in the different areas of dune lakes, it does seem that if the sources of contamination are eliminated, passive restoration might take place. Nevertheless Pérez-Caballero (2016) showed that lake D, which is being used by the municipal water and sanitation system as a stabilization lagoon, is not fulfilling the functions of such a lagoon for water treatment, as it presents an accumulation of nutrients. Thus passive restoration is limited to a certain degree of contamination.

In summary, the rural lakes have nitrate, ammonium and phosphorus concentrations values below those that indicate contamination (Table 3), while the urban lakes were eutrophic. Urbanization and the growth of the Port of Veracruz/Boca del Río exert significant, growing pressure. Despite being a Ramsar site and a natural reserve, there is still no management plan in place and the necessary measures have not been taken to stop its deterioration. Based on the data from this study, a diagnosis was made of 25 dune lakes as the basis for their classification, making it possible to establish the baseline for each of the lakes and group them according to the management and restoration measures they require. It is necessary to carry out the same exercise for the remaining 20 lakes. In general, we separated urban or semi-urban lakes from the rural ones, as they are subjected to different types of pressure and should be handled differently.

Group I. Lakes included in the Ramsar site and/or the natural reserve.

A. Urban with notable deterioration. In this set of lakes urbanization is very strong or increasing. These lakes receive domestic and storm water discharge, are eutrophic, and have poor vegetation management (Tarimoya, La Colorada, Laureles, Dos Caminos, Encanto, Ilusion, Caracol, Coyol, Ensueño, Lake D).
B. Semi-urban, in good condition. Strong or increasing urbanization. This lake still has adequate water quality, but there is a tendency to deterioration, and there is still no vegetation management (Conchas).
C. Rural, in good condition. Due to their size and good condition, they require a specific management plan; mainly because of their agricultural character (San Julián, Colorada).
D. Rural, in poor condition. This lake is located on private lands within the La Mancha El Llano Ramsar site, and is

in very poor condition due to silting, the invasive growth of plants, and the agricultural and cattle grazing activities on two sides (La Mancha).

Group II. Rural lakes that should be part of the Ramsar site and/or natural reserve, and are within the range of the Port and city influence. Due to their small size and good condition they should form part of a conservation area and have a management plan.

A) Small rural. The growth of the Port of Veracruz and the lack of a conservation area and management plan (Zendejas, Manguito, Abascal), along with their small size, will result in their disappearance, even though they are currently in good condition.
B) Rural with a tendency to urbanization. This lake is on private land that is being sold for urbanization (though the sale has had legal problems for over 10 years). Its future as an urban area must take into account the measures necessary to conserve it (Catalana).
C) Rural, with agriculture activities. These dune lakes require decisive management measures because of their agricultural character and the deterioration they are starting to experience (Minerva, La Palma) that must be prevented.

Group III. In this group there are only rural lakes that do not belong to the Ramsar site and have not been proposed as part of the nature reserve. They are not within the range of the Port expansion, and are in rather good condition. Due to their small size and acceptable conditions they should form part of the reserve, and because they are surrounded by farm land, they should have a management plan (Don Gilberto, Felix, Tolega, Jagüey, Ojite).

Management and restoration proposals

Table 4 lists a set of suggestions for the management of dune lakes, grouped as follows: a) recommendations based on the generation and application of rules, i.e., guidelines and existing regulations that should be part of the management plan, and above all, should be applied; b) recommendations for the construction of infrastructure; c) for conservation and restoration actions; d) environmental education, organization and training actions; e) for execution of the necessary legal actions. Each type of suggestion is explained in the Table, indicating the group of dune lakes for which they should be implemented. Dune lakes on private land in particular should be subject to formal agreements and economical support, or mechanisms that guarantee the preservation of their water quality under sustainable use.

A scheme with general management recommendations that can be applied to urban and rural lakes and wetlands, depending on their state of conservation is shown in Fig. 4. A set of recommendations is given for urban lakes with emphasis on the points that an urban plan should include. The set for rural lakes emphasizes control of livestock access, which will allow vegetation growth, and reduce nutrient inputs and silting. A third set is suggested for both types of lakes/wetlands and is focused on the participation of the local inhabitants or owners (in rural areas).

Given the changes that could arise, as suggested by different climate change scenarios, it is of paramount importance to maintain the ecosystem services that wetlands provide. For urban wetlands, restoring and maintaining the functions of flood protection (flood regulation in these cases) and water purification is imperative. Local participation should be promoted in activities around the urban lakes, and management plans should be discussed and explained to local inhabitants. In urban settings, the aesthetic, educational and recreation value and ecosystem services of dune lakes is also of great importance and should be emphasized. The transmission of disease by mosquitoes associated with water bodies is becoming a major health problem, so these ecosystems should contribute to reducing the habitat available to these organisms, rather than increasing them. Hence the importance of management plans that restore dune lakes along with participatory work to ensure that disease-carrying mosquito habitats are removed, while preserving the wetlands. Involving local inhabitants in environmental education and later in the care and preservation of wetlands is also important.

Lakes have also been considered effective sentinels for climate change, because they are sensitive to climate, respond rapidly to change, and integrate information about changes in the catchment area (Adrian et al. 2009). The water level in these lakes can indicate when the water table rises, and can thus serve as an indicator of flooding.

Finally, many of our protected natural areas and Ramsar sites require evaluation to establish their baseline values, better target conservation and restoration activities, and to make efficient use of financial resources. The management of these lakes should be based on rigorous studies and robust data to ensure that their condition improves. This study underlines the need for the joint effort of the municipalities involved, the government agencies in charge of water resources and wetlands, neighborhood associations and NGOs, as well as private owners and academia, in order to draw up a work plan that will lead to the recovery of these valuable wetland sites. This way, they will continue to fulfill their function of providing ecosystem services and maintain their aesthetic value to local inhabitants.

Table 4 Management recommendations for each group of dune lakes

		Group I A	Group I B	Group I C	Group 1 D	Group II A	Group II B	Group II C	Group III
Develop regulations as part of the management plan and apply them	Mark the limits of the current constructions and prevent their expansion over the lagoons (in the urban part of San Julián)	x	x	x			x		
	Close off legal and illegal domestic discharge and implement an economic support program to connect homes to the sewers or build septic tanks	x	x	x					
	Urban growth, expansion of the sea port and drainage construction, pipelines, etc. should not affect the existence or conditions of the dune lakes. Prior to execution, these projects need environmental impact analyses and urban plans should be updated.	x	x	x		x			
	Avoid using water for irrigation until there has been a study of the capacity of the lake to recover its level			x	x	x	x	x	x
Perform works and infrastructure	Construct various filters in the storm drains and add a wetland area to clean the water before it reaches the lake itself. Ensure that there are no water deposits where mosquitoes can proliferate	x	x	x		x	x		
	Build facilities so that local people can enjoy these sites	x	x	x					
	Build facilities so livestock can go down to drink water from the lakes at any given time or build external water troughs (establish a support program)			x	x	x	x	x	x
Restoration/ conservation	Design and allow for the growth of hydrophytes, especially those that are more efficient in the removal of nutrients (i.e. *Typha domingensis, Pontederia sagittata* and *Thalia geniculata*), maintaining controlled growth, forming belts that help trap sediment and filter water.	x	x	x	x	x	x	x	x
	Establish a permanent water quality monitoring system	x	x	x	x	x	x	x	x
	Restore the vegetation around the lake to avoid the passage of cattle and build fences to direct the movement of cattle. Restore dune lake borders once cattle has been redirected.			x	x	x	x	x	x
	Restore or conserve the hydrophyte vegetation and maintain it, ensuring that it does not cover the entire water body and that there is no invasion of exotic or undesirable flood-tolerant species			x	x	x	x	x	x
	Have plans for removing silt when necessary				x	x	x	x	x
Environmental education, organization and training	Establish an environmental education and participation program	x	x	x			x		
	Organize talks with landowners so that they know and value the importance of these wetlands			x	x	x	x	x	x
Legal actions	Establish agreements / management plan with community participation / or with owners	x	x	x	x	x	x	x	x
	Incorporate dune lakes into the natural protected area or Ramsar scheme and develop a participatory management plan					x	x	x	x

The criteria for each group are explained in the text. Group I A: Tarimoya, La Colorada, Laureles, Dos Caminos, Encanto, Ilusión, Caracol, Coyol, Ensueño, Lake D. Group I B: Conchas. Group I C. San Julián, Colorada. Group I D: La Mancha. Group II A: Zendejas, Manguito, Abascal. Group II B: Catalana. Group II C: Minerva, La Palma. Group III: Don Gilberto, Félix, Tolega, Jagüey, Ojite

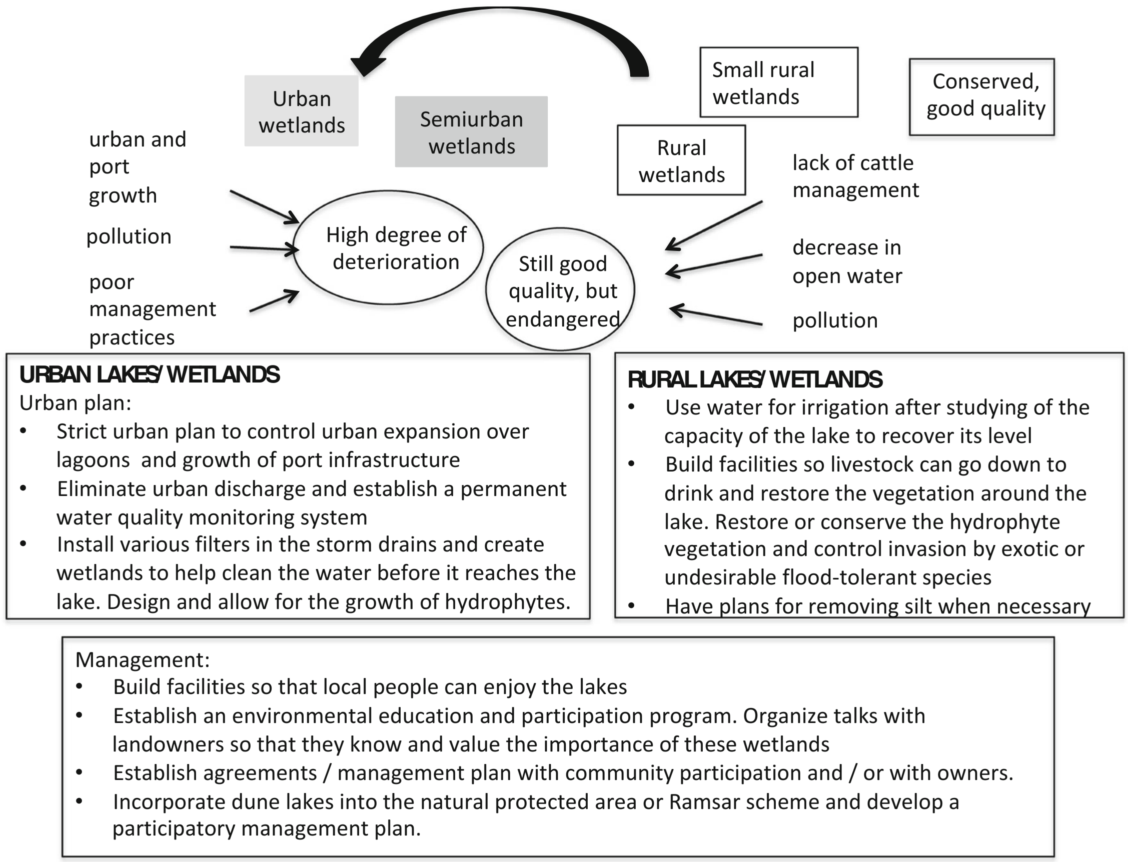

Fig. 4 Schematic management recommendations that can be applied to urban and rural lakes and wetlands, depending on their current state of conservation

Acknowledgements We thank the following institutions for their financial support: Consejo Nacional de Ciencia y Tecnología y Secretaría de Medio Ambiente (Instituto Nacional de Cambio Climático) Project No. 249270, Tecnológico Nacional de México (TecNM) project no. 4398.11-P and no. 5483.14-P, Veracruz Technological Institute, and Institute of Ecology A.C. We thank Roberto Monroy for help with the spatial analysis and for making the map, Víctor Vázquez for support in the laboratory, and Bianca Delfosse for revising the English.

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

References

Adrian R, O'Reilly CM, Zagarese H, Baines SB, Hessen DO, Keller W, Livingstone DM, Sommaruga R, Straile D, Van Donk E, Weyhenmeyer GA, Winder M (2009) Lakes as sentinels of climate change. Limnol Oceanogr 54:2283–2297

APHA-AWWA-WPCF (1990) Standard methods for the examination of water and wastewater. American Public Health Association, Washington DC

CONAGUA (Comisión Nacional del Agua) (2015) Atlas del Agua en México 2015. http://www.conagua.gob.mx/CONAGUA07/Publicaciones/Publicaciones/ATLAS2015.pdf. Accessed 16 Oct 2016

Curreli A, Wallace H, Freemna C, Hollingham M, Stratford C, Johnson H, Jones L (2013) Eco-hydrological requirements of dune slack vegetation and the implications of climate change. Sci Total Environ 443:910–919

De la Lanza G (1996) Situación actual de lagos y presas en México. In: Abarca, FJ, Cervantes M (eds) Manual para el Manejo y Conservación de los Humedales de México. Special Publication Secretaría del Medio Ambiente, Recursos Naturales y Ecología, U.S. Fish and Wildlife Service, Arizona Game and Fish Department and Wetlands International the Americas-Programa México, pp 1–26

DOF (Diario Oficial de la Federación) (2003) Segunda Sección. Secretaría de Medio Ambiente y Recursos Naturales. Acuerdo por el que se dan a conocer los límites de 188 acuíferos de los Estados Unidos Mexicanos, los resultados de los estudios realizados para determinar su disponibilidad media anual del agua y sus planos de localización. Published Friday 31, January 2003 (Viernes 31 de enero 2003)

Fukuhara H, Kawakami A, Shimogaito S (2003) Characteristics of nutrients in Lake Sagate, Japan, a shallow sand dune lake. Hydrobiologia 506-509:93–99

Gaceta Oficial de Veracruz CXCIV (2016) Num. Extraordinario 444, Folio 1289 Decreto para el establecimiento del Área Natural Protegida, en la categoría de Corredor Biológico Multifuncional Denominada Archipiélago de Lagunas Interdunarias de la Zona Conurbada de los Municipios de Veracruz y La Antigua, Ver. Published 7 November 2016

García ME (1987) Modificaciones al Sistema de Clasificación Climática de Köppen para Adaptarlo a las Condiciones de la República Mexicana. Editorial México. Mexico DF

Grootjans AP, Ernst WHO, Stuyfzand PJ (1998) European dune slacks: string interactions of biology, pedogenesis and hydrology. Trends Ecol Evol 13:96–100

Hernández ME (2010) Wetland soils as carbon sinks and sources of methane. Terra Latinoamericana 28:139–147
Hoz ZE, De la Lanza G (2000) Limnology and pollution of small, shallow tropical water-body (jagüey) in north-east Mexico. Lakes Reserv Res Manag 5:249–260
King RS, Richardson CJ, Urban DL, Romanowicz EA (2004) Spatial dependency of vegetation-environment linkages in an anthropogenically influenced wetland ecosystem. Ecosystems 7:75–97
Leentvaar P (1997) Communities of dune lakes. In: van der Maarel E (ed) Dry coastal ecosystems. General aspects. Elsevier, Amsterdam, pp 297–322
Legendre P, Legendre L (1998) Numerical Ecology. Elsevier, New York
Martínez ML, Moreno-Casasola P, Vázquez (1997) Effects of disturbance by sand movement and inundation by water on tropical coastal sand dune vegetation. Can J Bot 75:2005–2014
Martínez ML, Moreno-Casasola P, Espejel I, Jiménez-Orocio O, Infante-Mata D, Rodríguez-Revelo N (2014) Diagnóstico de las dunas costeras de México. CONAFOR. Mexico DF (http://www1.inecol.edu.mx/costasustentable/esp/documentos/publicacionestxt.htm#Libros)
Mc Cune B, Grace J (2002) Analysis of ecological communities. MjM software design. Gleneden Beach, Oregon
Moreno-Casasola P, Infante Mata D (2010) Veracruz. Tierra de Ciénagas y Pantanos. Gobierno del Estado de Veracruz para la Conmemoración de la Independencia Nacional y de la Revolución Mexicana- Universidad Veracruzana. Xalapa, Veracruz, Mexico (http://www1.inecol.edu.mx/costasustentable/esp/documentos/publicacionestxt.htm#Libros)
Moreno-Casasola P, Vazquez G (1999) The relationship between vegetation dynamics and water table in tropical dune slacks. J Veg Sci 10(4):515–524
Neri-Flores I, Escolero Fuentes OA, Pérez Torres S, Riquer Trujillo G (2014) Inundaciones por agua subterránea en zonas costeras. Caso de estudio: acuífero de Veracruz. Bol Soc Geol Mex 66:247–261
Peralta-Peláez LA (2007) Diseño de un índice de integridad biótica para los lagos interdunarios de la región costera central del estado de Veracruz, México. Dissertation. Institute of Ecology A.C., Mexico
Peralta-Peláez LA, Moreno-Casasola P (2009) Composición florística y diversidad de la vegetación de humedales en los lagos interdunarios de Veracruz. Bol Soc Bot Mex 85:89–101
Peralta-Peláez LA, Deloya C, Moreno-Casasola P (2007) Insectos acuáticos asociados a las lagunas interdunarias de la región central del estado de Veracruz, México. Neotrop Entomol 36(3):342–355
Peralta-Peláez LA, Moreno-Casasola P, López-Rosas H (2014) Hydrophyte composition of dune lakes and its relationship to land-use and water physicochemistry in Veracruz, Mexico. Mar Freshw Res 64:1–15
Pérez-Caballero KH (2016) Evaluación del servicio ambiental de la laguna "D" como laguna de estabilización. Dissertation. Instituto Tecnológico de Veracruz, Mexico
Primeau S (2004) Coastal freshwater wetlands development in Mexico: a 4500-year record of succession from Laguna La Mancha, Veracruz. Dissertation, University of Waterloo, Canada
Ranwell DS (1972) Ecology of salt mashes and sand dunes. Chapman and Hall, London
Rhymes J, Wallace H, Fenner N, Jones L (2014) Evidence for sensitivity of dune wetlands to groundwater nutrients. Sci Total Environ 490: 106–113
Sarabia D (2004) Sistema lagunar de la ciudad de Veracruz: propuesta de manejo bajo la visión de proyectación y gestión ambiental. Doctoral Thesis. Colegio de Posgraduados, Campus Veracruz. Universidad de Chapingo, Mexico
Siemens A, Moreno-Casasola P, Sarabia C (2006) The metabolization of wetlands by the city of Veracruz, Mexico. J Lat Am Geogr 5:7–29
Spalding M, Ruffo S, Lacambra C, Meliane I, Hale L, Shepard C, Beck M (2014) The role of ecosystems in coastal protection: adapting to climate change and coastal hazards. Ocean Coast Manag 90:50–57
StatSoft Inc (2004) Statistica (data analysis software system), ver. 7. www.statsoft.com
Torres-Orozco B, Jiménez-Sierra C, Buen Abad JL (1994) Caracterización limnológica de dos cuerpos de agua tropicales de Veracruz, Mexico, Anales del Instituto de Ciencias del Mar y Limnología. Universidad Nacional Autónoma de México 1-2:1–19
Vázquez G (2004) The role of algal mats on community succession in dunes and dune slacks. In: Martínez ML, Psuty NP (eds) Coastal dunes. Ecology and conservation. Ecological studies, vol 17. Springer-Verlag, Berlin, pp 189–203
Wetzel RG (1981) Limnología. Omega, Barcelona
Whigham DF, Jordan TE (2003) Isolated wetlands and water quality. Wetlands 23:541–549
Whigham DF, Chitterling C, Palmer B (1988) Impacts of freshwater wetlands in water quality: a landscape perspective. Environ Manag 12:663–671
Yetter JCh (2004) Hydrology and geochemistry of freshwater wetlands on the Gulf coast of Veracruz, México. Dissertation. University of Waterloo, Canada
Zar JH (1999) Biostatistical analysis. Prentice Hall, Englewood Cliffs