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ORIGINAL ARTICLE

Environmental hydrogeology of the southern sector of the Samborombon Bay wetland, Argentina

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Abstract The Samborombon Bay wetland is located on the west margin of the Rio de la Plata estuary, in the Province of Buenos Aires, Argentina. This paper analyses the geological, geomorphologic, soil and vegetation characteristics of the southernmost sector of this wetland and their influence on surface water and groundwater. The study area presents three hydrologic units: coastal dunes, sand sheets and coastal plain. Coastal dunes and sand sheets are recharge zones of high permeability with well-drained, non-saline soils, and a few surface water flows. Changes in the water table are related to rainfall. Groundwater in coastal dunes is Ca–Mg–HCO_3 to Na–HCO_3, and of low salinity (590 mg/l). Groundwater in sand sheets is mainly Na–HCO_3 with a salinity of about 1,020 mg/l. The coastal plain exhibits medium to low permeability sediments, with submerged saline soils poorly drained. Groundwater is Na–Cl with a mean salinity of 16,502 mg/l. A surface hydrological network develops in the coastal plain. Surface water levels near the shoreline are affected by tidal fluctuations; far from the shoreline water accumulates because of poor drainage. Both sectors have Na–Cl water, but the former is more saline. Human intervention and sea level rise may affect the wetland severely.

Keywords Samborombon Bay · Argentina · Wetlands · Surface water · Groundwater

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Introduction

Wetlands are hydrological ecosystems with characteristics that include water storage, regulation of surface and groundwater flows, discharge and recharge of aquifers, and natural retention of nutrients and contaminants. In these environments water budget is mainly associated with rainfall, runoff and groundwater flow, but wetlands located near coastal zones may also have a certain amount of seawater inflow through tidal influence. Water dynamics is determined by the soil and geological properties associated with the geomorphology of the wetland. On the other hand, the geomorphologic characteristics can affect the biogeochemical processes, the drainage network and the soil development (Johnston et al. 2001). The hydrological characteristics of wetlands have been analyzed by several investigators (Hunt et al. 1999; Winter 1999; Hayashi and Rosenberry 2002; Weng et al. 2003; Ladouche and Weng 2005).

Although wetlands are distributed all along the Argentinean coast, the most typical and extensive are those at Samborombon Bay in the Province of Buenos Aires (Fig. 1). The Samborombon Bay lies in the central part of the Salado River basin depression and extends for more than 100 km on the west margin of the Rio de la Plata, the

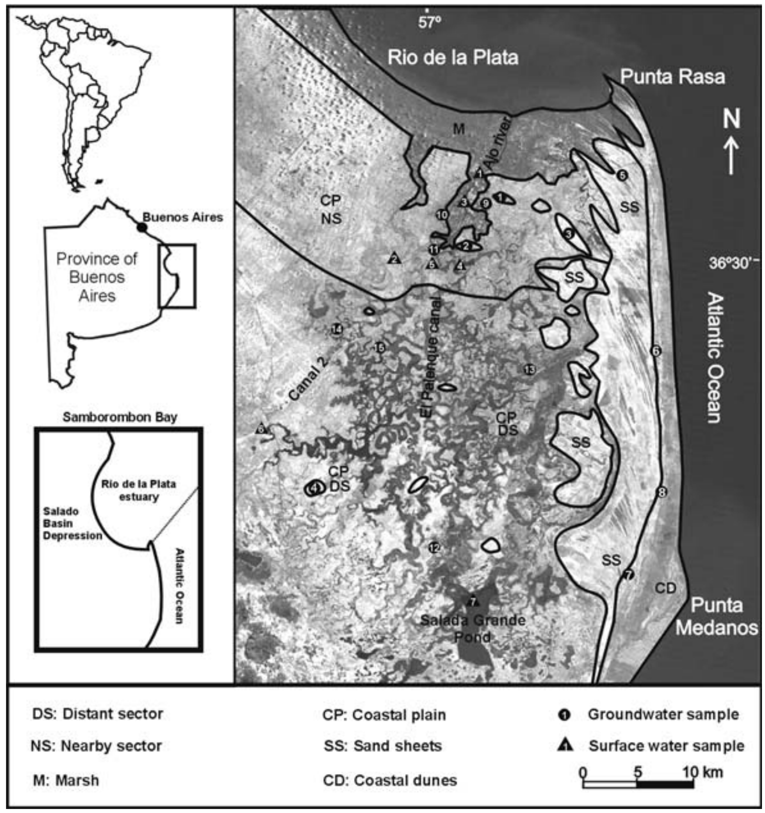

Fig. 1 Location map of the study area showing hydrogeological units and water sample points

most prominent estuarine environment in Argentina. The adjacent hinterland is very flat and the topographic gradient low. This portion of the Salado depression is occupied by Pleistocene and Holocene coastal and marine deposits corresponding to Last Interglacial and the Postglacial marine transgressions, respectively (Ameghino 1889; Frenguelli 1950; Fidalgo et al 1973). At Samborombon Bay a brackish marsh is present behind an extensive muddy, tidal flat. Frequent strong southeasterly winds push the Rio de la Plata waters upriver, hindering drainage into the bay and causing severe flooding all along the estuary shore. These storm surge events, locally known as ''sudestadas'' (southeasters), are characterized by a gradual increase in the SE-SSE wind velocity accompanied by a sky completely covered by nimbostratus and persistent rainfall (D'Onofrio et al. 2007). Because of these stormy events the agricultural activities at the Samborombon Bay hinterland are somewhat restricted.

The southernmost portion of the Samborombon Bay wetland is located at the transitional zone between the outlet of the Rio de la Plata and the Atlantic Ocean (Fig. 1), and so it presents features from both the river and marine environments. The purpose of this work is to describe the geological, geomorphologic, soil and vegetation characteristics, and their influence in surface water and groundwater flow, in this portion of the Samborombon Bay wetland.

There are no previous studies on the environmental hydrogeology of the whole Samborombon Bay wetland with the level of details shown in this work for the southernmost portion of this marshy swamp. Therefore, the above-mentioned environmental characteristics are useful for predicting the hydrological behavior of similar regions with scarce data.

Study area

The study area extends for about 33 km of coastline in the southernmost portion of the Samborombon Bay wetland (Fig. 1). According to the classification of Thornthwaite (1948), the climate is sub-humid to humid, mesothermal, with scarce to null water deficiency. The annual average temperature and precipitation are 15.2°C and 1,078 mm, respectively, the largest precipitations occurring during the summer. The relief is plain, with a slope of 0.01% and an average altitude of 1.6 m over mean sea level (MSL). Isolated, mild hills not higher than 2.5 m over MSL spread throughout the area. To the East, and limiting the wetland zone, a series of coastal dunes develop with altitudes between 5 and 30 m over MSL. The area drains into Samborombon Bay through the Canal 2 and the El Palenque Canal, both flowing into the Ajo River (Fig. 1), and also through a network of small creeks that become connected during rainy periods. The Canal 2 and the El Palenque Canal are two of a series of drainage canals towards Samborombon Bay constructed by the Public Works authorities from the beginning of the twentieth century because of the recurrence of historic floods. However, results have not been optimal, as floods have occurred ever since. Tidal ranges of about 1.5 m hinder discharge into the bay.

Methodology

The geologic, geomorphologic and soils features and the associated flora were analyzed from topographic maps, satellite images, aerial photographs and field works. Soil classification was made according to the U.S.D.A Soil Taxonomy (1999). Sampling points and measurements of surface water and groundwater were selected to verify the relation of the hydrologic conditions to the above-mentioned features. The data correspond to phreatic water samples from a net of wells, mills and hand pumps, and to surface water samples from the main drainage canals. Samples were obtained periodically every 6 months from July 2004. Fifteen sampling points for groundwater and seven for surface water were selected from a total sampling net of 60 points to characterize the study area. The collection, preservation and chemical analysis of water samples were made following the standard methods given by the American Public Health Association (APHA 1998). The Na^+ and K^+ cations were measured using a flame photometer. Total hardness as calcium carbonate $CaCO_3$, calcium (Ca^{2+}), carbonate (CO_3^{2-}), bicarbonate (HCO_3^-) and chloride (Cl^-) were determined by volumetric methods, whereas Mg^{2+} was calculated from total hardness and calcium. Sulphates (SO_4^{2-}) were measured by nephelometry, and nitrates (NO_3^-) by selective electrode technique. The amount of total dissolved solids (TDS or salinity) was measured gravimetrically. The electrical conductivity and pH of water samples were determined immediately after their collection in the field using a portable kit. Except for pH, a dimensionless number, all other constituents are expressed in mg/l. Electrical conductivity is given in μS/cm.

Results and discussion

Geology and geomorphology

Surface geological units are composed of psammitic-pelitic sediments of the Pleistocene and Holocene ages. These sediments originate in successive displacements of the shoreline due to sea level oscillations (Parker 1979; Violante et al. 1992, 2001). The present configuration is the result of a simultaneous development of a sand spit, salt and brackish marshes, muddy tidal flats and channels. The spit originates in the regional northwards littoral drift and migrates to the north. Punta Rasa is at the end of the spit (Fig. 1). To the west of the spit a coastal plain develops from marshes occupied by pelitic sediments. From a lithological point of view two different sectors may thus be defined: the eastern sector composed of the sandy sediments of the spit, and the central-west sector formed by the pelitic sediments of the coastal plain. The sandy sediments form a system of coastal dune ridges, whereas thin sand sheets from aeolian transport deposit over the pelitic sediments of the coastal plain (Figs. 1, 2).

Hydrogeology

According to the geomorphology of the study area it is possible to define three different hydrogeological units: coastal dunes, sand sheets and coastal plain (Fig. 1).

Coastal dunes

This unit consists of beach dune ridges with a north–south orientation and parallel to the coastline. Fine and shelly sands predominate at the surface, followed downwards by shelly sands and gravels, and finally by medium to coarse sands. The permeability is high, between 7 and 50 m/day (Gonzalez Arzac et al. 1992). A thick clayey pelitic package with scarce sand and a medium to low permeability lies below (Table 1).

Sand sheets

Sand sheets develop in a fringe to the west of the coastal dune ridges, parallel to them and spread in small sectors over the depressed zone. The granulometry decreases towards the west, where sheets with a large proportion of silty material are found (Dangavs 1983). The upper layer exhibits shelly fine sands with high permeability. Silty and clayey sediments of medium permeability are found downwards, followed by silty clayey sediments and low permeability clays (Table 2).

Coastal plain

The coastal plain covers the west and central sectors of the study area and includes old tidal channels, the flood plain, salt marsh swamps and the present tidal plain. Silty and clayey sediments of medium permeability are found at the surface, with silty clayey and clayey sediments of medium to low permeability below (Table 3).

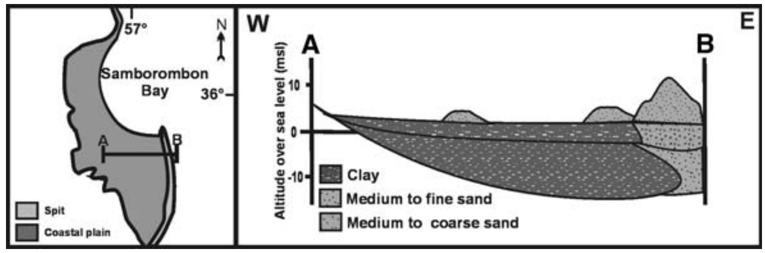

Fig. 2 Schematic geological section of the study area

Table 1 Lithology and hydrogeological characteristics of coastal dunes

Lithology	Relative permeability	Approximate thickness (m)
Fine sands with shell sand	High	7–10
Sands with shell sand and gravel	High	5–7
Medium and sharp sands	High	4–10
Clays and fine sands with clayey matrix	Medium to low	3–7
Clays with sand intercalations	Medium to low	4–8
Marls and clays with sand intercalations	Low	Non determined

Table 2 Lithology and hydrogeological characteristics of sand sheets

Lithology	Relative permeability	Approximate thickness (m)
Fine sands with shell sand	High	2–3
Silt and clays with sands	Medium	3–5
Clays and fine sands with clayey matrix	Medium to low	3–7
Clays with sand intercalations	Medium to low	4–8
Marls and clays with sand intercalations	Low	Non determined

Table 3 Lithology and hydrogeological characteristics of coastal plain

Lithology	Relative permeability	Approximate thickness (m)
Silt and clays with sands	Medium	3–5
Clays and fine sands with clayey matrix	Medium to low	3–7
Clays with sand intercalations	Medium to low	4–8
Marls and clays with sand intercalations	Low	Non determined

Soil

Three soil types are basically recognized: well-drained, poorly drained and submerged soils. Table 4 shows their main characteristics and relation to the geomorphologic units. Well-drained soils are found in coastal dunes and sand sheets, whereas poorly drained and submerged soils develop in the coastal plain. Because of their low-lying topography the coastal plain soils are saturated during part of the year. These soils are associated with old tidal channels and their marginal ridges, and with depressed sectors. Submerged soils are associated with marsh swamps, tidal channels with semi-permanent water and ponds and creeks with permanent water. Overflowing originates in rain, runoff and water table rise.

Vegetation

Vegetal communities of *Celtis spinosa*, *Jordina rhombifolia*, *Acacia caven* and *Scutia buxifolia*, associated with well-drained soil environments, develop in topographically high zones.

Hydrohalophite communities of *Distichilis spicata*, *Salicornia ambigua*, *Sporobolus sp.* and *Polypogon sp.* develop in low-lying saline soils with poor drainage. Halophite species such as *Salicornia ambigua* and *Paspalum vaginatum* predominate in environments characterized by the accumulation of silty clayey sediments on bare soils periodically flooded. Associations of *Scirpus californicus*, *Typha latifolia*, *Solanum malacoxylum* and *Spartina sp.* are observed in small creeks and ponds where water accumulates for longer periods.

Hydrochemistry

Variations in salinity of both surface water and groundwater are basically related to the concentrations of chloride, sodium, sulphate and bicarbonate ions. Table 5 shows the results from a selection of the more representative sample points (Fig. 1).

Surface waters

Because of the high permeability of the soil there are no signs of surface drainage in coastal dunes and sand sheets. Instead, a surface hydrological system is clearly seen in the coastal plain, where the low permeability of the sediments and the small topographic gradient originate a drainage

Table 4 Soil characteristics in the study area

Drainage	Geomorphology	Soil	Texture	Permeability	Alkalinity	Salinity	Hydromorphism signs
Well drained	Coastal dunes	Entic hapludoll	Sandy	High	Alkaline	Non saline	None
	Sand sheets	Thapto natric hapludoll	Sandy–silty	High	Slightly alkaline	Non saline	None
		Typic natraquert	Silty	Moderate	Alkaline	Slightly saline	None
Poorly drained	Coastal plain	Typic natraquert	Silty	Moderate	Alkaline	Slightly saline	Fe motted at the base
		Chromic salaquent	Clayey	Low	Alkaline	Strongly saline	Fe–Mn motted
Submerged		Undifferenced	Clayey	Low	Alkaline	Saline	Signs of gley
		Typic natraquert	Clayey	Low	Alkaline	Strongly saline	Fe–Mn motted

Table 5 Physicochemical characteristics of surface water and groundwater in the study area

Hydrogeological units	Sample no.	Cond. (μS/cm)	Salinity (mg/l)	Ph	$CO_3^{=}$ (mg/l)	HCO_3^- (mg/l)	Cl^- (mg/l)	$SO_4^{=}$ (mg/l)	NO_3^- (mg/l)	Na^+ (mg/l)	K^+ (mg/l)	Ca^{++} (mg/l)	Mg^{++} (mg/l)
Groundwater													
Sand sheets	1	5,430	3,140	7.3	0	708	1,420	157	33	877	162	218	31.6
	2	5,850	3,725	7.7	0	659	1,619	111	17	1,000	88	380	6
	3	2,500	1,670	7.5	0	738	362	127	4	410	62	96	10.9
	4	1,535	960	7.8	0	695	163	52	3	526	41	52	39
	5	1,590	1,080	7.5	0	55	188	47	80	220	57	96	24
Coastal dunes	6	1,450	830	7.7	0	494	270	8	5	210	18	76	35
	7	715	440	7.6	0	445	28	51	2	70	4.8	68	34
	8	290	500	8.1	0	183	84	26	3	20	1.3	52	36
Coastal plain	9	38,000	25,600	7.2	0	980	13,135	1,600	110	7,325	200	1,800	255
	10	20,800	13,525	6.6	0	598	6,745	817	106	3,361	143	520	450
	11	5,130	3,200	7.6	0	1,513	880	262	4	1,150	35	44	25.5
	12	30,400	19,465	7.8	0	1,196	9,585	1,140	86	5,475	155	400	644
	13	44,000	30,795	7.1	0	1,135	15,052	3,251	150	8,375	235	1,920	486
	14	17,600	10,985	7.3	0	891	5,467	846	61	3,200	114	480	219
	15	19,000	11,950	7.5	0	1,287	5,609	1,270	50	3,430	90	400	243
Surface water													
Coastal plain nearby sector	1	6,730	4,345	7.7	0	172	2,130	332	22	1,190	58	116	123
	2	6,430	4,060	8.6	42	451	1,576	578	35	1,150	40	76	120
	3	2,360	1,345	7.7	0	178	543	196	3	356	27	132	9.8
	4	2,590	1,495	7.6	0	179	611	196	3	388	29	140	9.8
	5	962	575	7.9	0	156	167	79	4	142	12	40	7.2
Coastal plain distant sector	6	2,290	1,315	8.3	5.4	335	437	224	6	360	18	124	10.9
	7	3,320	2,200	8.9	24	488	870	63	7	526	41	48	80

network that includes many temporary and permanent ponds. These ponds are connected through small creeks, particularly during rainy periods. The hydrological regime and the hydrochemical characteristics of the coastal plain depend on the nearness and connection of the streams with the Rio de la Plata estuary. In this regard, it is possible to draw a distinction between a sector far from the coastline and without connection with the estuary, called DS (distant sector), and another sector in direct contact with the estuary, called NS (nearby sector) (Fig. 1).

Far from the coastline the surface water regime is closely related to precipitation. The excess of water is drained into Samborombon Bay through the El Palenque Canal. Waters are Na–Cl with average salinity of 1,757 mg/l. Variations in salinity depend on the difference between precipitation and evaporation. Near the coastline the streams and channels (natural and artificial) are influenced by the tidal fluctuations at the estuary. Inflow is favored by the extremely gentle topographic gradient. These waters contain Na–Cl with average salinity of 2,811 mg/l. The water in Canal 2, which comes from outside the region, contains less Na–Cl with salinity of 945 mg/l, and discharges into the Ajo River.

Figure 3 shows a Piper diagram (1944) of the chemical characteristics of surface waters. It is seen that waters from the coastal zone have a more Na–Cl character than those from inland zones. Waters from the Canal 2 contain the least sodium chloride level. Surface waters show an increasing salinity towards the estuary, whether or not they discharge into it.

Groundwater

Coastal plain

In the coastal plain, groundwater flow direction changes according to the level of surface water. If the level of surface water is high, because of high tide, a humid period, or water accumulation in channels, the flow is towards the water table. Conversely, if the level of surface water is low, groundwater discharges into streams (Fig. 4a). Near the shoreline, the daily changes in surface water level due to the tide originate variations in the flow direction (Fig. 4b). Infiltration from excessive rain has also its influence on the water table. Groundwater contains Na–Cl, with mean salinity of 16,502 mg/l (Fig. 5). Salinity is related to the dilution of salts from estuarine and marine sediments.

Sand sheets

Groundwater in sand sheets is closely related to rainfall, which constitutes the recharge of the system. The discharge occurs into the coastal plain. Sand sheets thicker than 2.5 m have Na–HCO_3 waters with salinities on the order of

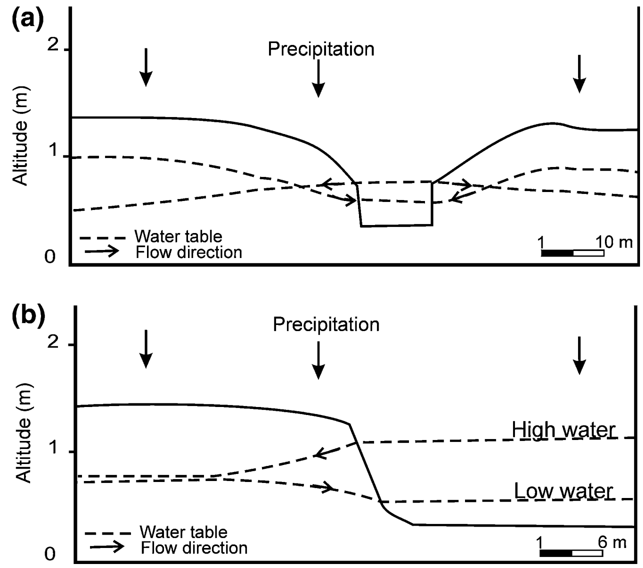

Fig. 4 Typical sections of Canal 2 (**a**) and the Ajo River (**b**) showing the position of the water table and changes in water flow direction

1,020 mg/l. In less thick sheets waters contain Na–Cl and the salinity increases to 2,845 mg/l (Fig. 5).

Coastal dunes

As in sand sheets, groundwater recharge depends on precipitation. The discharge occurs in the coastal plain and the sea. The waters are Ca–Mg–HCO_3 to Na–HCO_3-containing and are less saline, with values about 590 mg/l (Fig. 5).

General remarks

To preserve the natural conditions of the study area (and of the whole Samborombon Bay wetland) it is necessary to

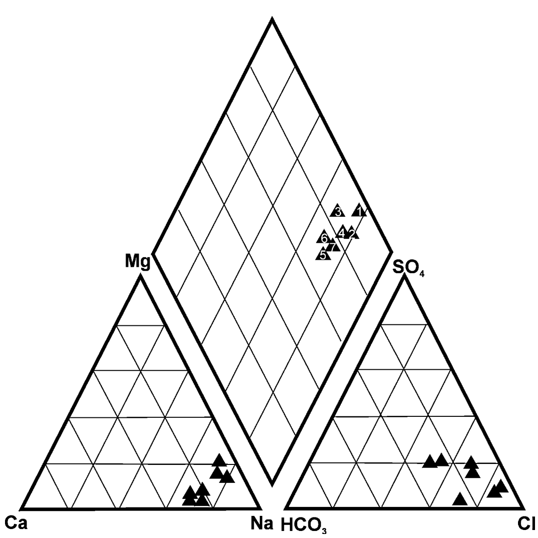

Fig. 3 Piper diagram for surface waters

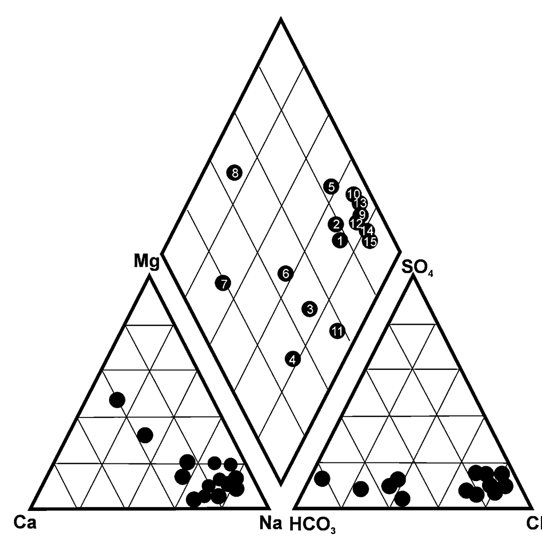

Fig. 5 Piper diagram for groundwater

predict the dynamics and quality of water resources. This is a difficult task because of the scarcity of historical hydrological and hydrochemical data. In view of these facts the evaluation of the geological, geomorphologic, soil and vegetation characteristics seems a valuable tool for predicting future hydrologic scenarios in the presence of natural or anthropic events. The Samborombon Bay wetland is a natural reserve subjected to periodic floods due to rainfall, runoff, tidal fluctuations and storm surges, where the excess of precipitation drains naturally into the estuary. This salt marsh swamp is extremely productive and exhibits a high biodiversity. The construction of regional drainage canals to mitigate the effect of floods (such as Canal 2 and El Palenque Canal) can be a significant factor in the degradation of this ecosystem by affecting its hydrological budget.

Any industrial development program should take into consideration the hydrological characteristics of the wetland, solve satisfactorily the problem of water supply and effectively treat the resultant sewage. Because freshwater resources are scarce, the volumes to be drawn from pumping wells should be controlled in order to avoid saltwater encroachment due to a landward migration of the saltwater–freshwater interface.

Relative sea level rise, as predicted by the IPCC (2007), would result in major damage in low-lying, flood-exposed plains such as the Samborombon Bay wetland. D'Onofrio et al. (2007) have determined a relative sea level rise of +1.68 ± 0.05 mm/year for Buenos Aires, the capital city of Argentina, located on the west margin of the Rio de la Plata estuary to the north of Samborombon Bay (Fig. 1). Due to the low topographic slopes of the study area, extensive parts of the coastal plain could remain permanently flooded. This would modify the present land occupation as well as the flow and chemical conditions of surface waters and groundwater. Sea level rise could also affect significantly the scarce freshwater reserves in sand sheets and, to a lesser extent, in coastal dunes. In addition, episodic floods due to storm surges could become more severe, particularly if the surge height and duration increase as a result of climate change. Under these conditions the Samborombon Bay wetland would be affected by migration and recolonization. Although it is likely that inland migration would keep pace in vertical growth relative to the rate of sea level rise, human intervention can modify negatively the natural response capacity of the wetland.

Conclusions

The hydrologic units into which the southernmost portion of the Samborombon Bay wetland may be divided, i.e., coastal dunes, sand sheets and coastal plain, allow this salt marsh swamp to be characterized as highly vulnerable with respect to human activities. The drainage of excessive water volumes through a system of canals, as well as the disposal of sewage can severely affect the wetland behavior and its biological activity. Most of the surface water and groundwater resources are unfit for drinking because of their high salinity. The shallowness of the water table in freshwater reservoirs and their high permeability make them extremely vulnerable to contaminants. Consequently, any urban or industrial development must consider a sustainable management of water resources.

Due to the extremely gentle topographic gradient of the whole Samborombon Bay wetland, minor positive variations in sea level may aggravate the impacts from storm surges and cause the flooding of extensive areas with consequent land loss and a decrease in freshwater reserves (particularly in sand sheets). The natural adaptive response of the wetland to sea level rise might be seriously hindered by the present human activities.

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