Surface water and groundwater response to the tide in coastal wetlands: Assessment of a marsh in the outer Río de la Plata estuary, Argentina

Eleonora Carol †, Eduardo Kruse †, Macarena Tejada∞

† Consejo Nacional de Investigaciones Científicas y Técnicas. Facultad de Ciencias Naturales y Museo, Universidad Nacional de La Plata, Calle 64 #3, 1900, La Plata, Argentina
eleocarol@fcnym.unlp.edu.ar
kruse@fcnym.unlp.edu.ar

∞Physical Geography University of Pablo de Olavide, 41013 Sevilla, Spain
mtejtej@upo.es

www.cerf-jcr.org

www.JCRonline.org

ABSTRACT

Carol, E; Kruse, E and Tejada, M, 2013. Surface water and groundwater response to the tide in coastal wetlands: Assessment of a marsh in the outer Río de la Plata estuary, Argentina, *Proceedings 12th International Coastal Symposium* (Plymouth, England), *Journal of Coastal Research*, Special Issue No. 65, pp. 1098-1103, ISSN 0749-0208.

On the coast of the outer Río de la Plata estuary (Argentina) there is a vast coastal wetland occurring in a marsh environment. The hydrodynamics of this wetland is subject to a semidiurnal microtidal regime which causes a wedge of estuary salt water to penetrate below the freshwater coming from continental discharge. This paper analyzes the hydrodynamics of surface and groundwater, and it assesses how anthropogenic changes affect the natural hydrological behavior of the coastal wetland in the southern sector of the outer Río de la Plata estuary. Water level and temperature measurements were carried out on water from the canals flowing into the estuary and the phreatic aquifer located in the marsh. The salinity of the water column was measured at one high tide which was above and one which was below the regional groundwater discharge level. The results show that in natural conditions the wetland has a complex hydrological behavior conditioned by the tidal flow. Surface and groundwater saline stratification is a distinctive characteristic, and the variations in level, temperature and salinity of groundwater depend on its interaction with estuary and continental water. At present, 47 % of the marsh is excluded from the tidal cycle due to anthropogenic action (levees, roads and canals with floodgates), causing a major alteration to the hydrological behavior and the environmental characteristics of the wetland.

ADDITIONAL INDEX WORDS: *intertidal wetlands, surface water–groundwater interaction, water salinity, anthropogenic changes.*

INTRODUCTION

Marshes are intertidal wetlands whose environmental characteristics depend on the relationship between the river–estuary–sea water systems. Their development and extension are associated with the tidal characteristics, deposition, sediment types, freshwater inflow and coastal structure (Vernberg 1993, Montalto et al., 2006).

The spatial and temporal variations in surface and groundwater quality and flow in connection with the tidal flow in coastal wetlands are relevant not only due to their environmental implications, but also because they provide the necessary basis for the sustainable management of natural resources.

In recent years, the hydrological study of these environments has increased in importance worldwide, which is why numerous studies have been carried out on the basis of mathematical modelling and field surveys. Even though surface water–groundwater interaction has been studied on the basis of mathematical models (Yuan and Lin, 2009, Lenkopane et al., 2009, Xin et al., 2011), the bibliographic references on field studies are limited (Cao et al., 2012, Carol et al., 2012). As regards field studies, they are mainly oriented towards the analysis of data on surface water (Chen et al., 2000) or groundwater (Cave and Henry, 2011, Taniguchi et al., 2007), and not towards the interaction between them.

The outer Río de la Plata estuary has a semi-diurnal microtidal regime with daily variations. A wedge-shaped layer of saltwater flowing from the sea penetrates below the freshwater from the river (Acha et al., 2008). The littoral of the Samborombón Bay, located on the Argentinian coast (Fig. 1), covers a coastal plain and marsh area in which an intertidal wetland — declared a Ramsar site in 1997 — occurs.

In the southern section of the bay there is a vast marsh (approximately 126 km^2) associated to the banks of the Ajó River, as well as several tidal channels which allow the tidal wave to propagate from the estuary towards the continent (Fig. 1). The El Palenque Canal, draining the coastal plain area to the south, and the Canal 2, carrying allochthonous water from a higher area located to the southwest, are the major inflowing canals (Fig. 1).

DOI: 10.2112/SI65-186.1 received 07 December 2012; accepted 06 March 2013.

Along the canals, before they flow into the Ajó River, there are floodgates preventing water inflow from the estuary and regulating the flow of the water surplus towards the bay.

Figure 1. Location of the study area and marsh areas modified by anthropogenic action (indicated in red). The white boxes show the location of the images in Figures 3a (a), 3b (b) and 5 (c).

The climate is humid temperate; the average rainfall for the 1889–2011 period was 940 mm/year, with a maximum value of 1634 and a minimum of 380 mm/year. Such annual rainfall variations cause the occurrence of dry and wet periods. The potential evapotranspiration is 770 mm/year and the average temperature is 14.6 °C (Carol et al., 2009).

Soils are saline with poor drainage (Carol et al., 2008) and unfit for agriculture, which is why the main economic activity is livestock farming. The expansion of such an activity towards intertidal areas led to the construction of engineering works in order to prevent tidal inflow, reduce the flooded surface and increase the extension of grazing land.

It is the objective of this work to assess the response of surface and groundwater to the tidal flow in both natural areas and in those modified by anthropogenic action in the coastal wetland located in the Ajó River marsh, in the southern sector of the outer Río de la Plata estuary.

METHODOLOGY

SPOT (Système Pour l'Observation de la Terre) satellite images of 2010 and 15-m resolution were interpreted in order to identify the natural marsh areas and those affected by anthropogenic action. Images were georeferenced, generating a mosaic, which made it possible to digitize the marsh areas and calculate the affected ones. These data were integrated into a geographic information system (ArcGIS). Field surveys were carried out to verify the interpretation of the images and assess the environmental and hydrological characteristics.

The dependence of surface water–groundwater interaction on tidal flow was studied on the basis of level, temperature and salinity measurements in surface water (SW) and shallow groundwater (GW), in a natural area (SW1 and GW1) and in another one modified by man (SW2 and GW2, Fig.1). The groundwater sampling points correspond to monitoring wells located in the marsh adjacent to the surface water measurement points. The drilling of the wells located in the marsh was done with a hand auger to a depth of 3 m. Inside every well, a slotted 2-inch PVC screen was fitted and backfilled with gravel. The height of the pipe prevents water inflow in case the marsh is completely flooded at high tide. Hydrometric and water table gauging was carried out by means of manual probes (hourly measurements) and level and temperature data loggers (Solinst Leveloggers Model 3001) with measurements every 10 min. Data loggers (Solinst Barologgers) were used to correct the data of the Leveloggers. The records analyzed in this work were obtained in the period ranging from 9 April, 2011 to 9 May, 2011. The sea level determined by the Instituto Geográfico Nacional (National Geographic Institute, Argentina) was used to set all surface and subsurface measurement points, which was carried out by means of a Pentax AL-240 Automatic Level with an accuracy of ± 0.02 m. The water level data are expressed in meters above sea level (m asl).

The salinity of the water in the river, the canals and the aquifer was determined by means of a manual probe (Solinst TLC Meter Model 107) every 50 cm down the water column. Salinity measurements were carried out between low and high tide in two tidal cycles, one of them when the estuary water level was above the regional groundwater discharge level (18 April, 2011) and another one below (10 April, 2011). This level refers to the lowest hydraulic head level in the whole groundwater system which flows towards and discharges into the Ajó River and the canals. During the sampled period, such a level fluctuates between 0.47 and 0.56 m asl, using for this work a mean value of 0.50 m asl. Likewise, for the analysis of the marsh areas excluded from the tidal flow, salinity data collected in seasonal measurements (dry and wet periods) and recorded periodically since 2006 were used.

RESULTS

Natural hydrological conditions

In the natural areas, the marsh is periodically flooded by the high tide. In the sampled period, the surface water level (SW1) shows variations between −1.07 and 1.20 m asl, with mean tidal ranges close to 1 m (Fig. 2). In shallow groundwater, the level also shows periodic fluctuations depending on the tide. Such fluctuations only occur when the surface water level is higher than the regional groundwater discharge level (levels above 0.50 m asl). Groundwater level rises associated with the high tide of more than 0.50 m have been recorded (Fig. 2).

As regards the wetland, the water table is shallow (i.e., less than 1 m below ground level) with a predominance of silty-clayey sediments with low hydraulic conductivity. The vertical hydraulic conductivity of the sediments and the penetration of the tidal flow into the aquifer are increased by the presence of macropores, created by the burrowing of the large population of crabs inhabiting this environment. At high tide, when the marsh is flooded, the tidal flow enters the aquifer, with water infiltrating vertically through the macropores and causing the water table to rise. At low tide, as the water level of the river decreases, the water table tends to recover its position by discharging into the river in a sub-horizontal direction. At low tide, as a result of the decrease in water level in the river, the water table discharges into the river in a sub-horizontal direction and tends to recover its position. The low permeability of the silty sediments of the marsh — and not the macropores of the crab burrows — conditions this sub-horizontal groundwater flow, which is why at low tide the transference of groundwater towards the river is very slow. This is made evident by the occurrence of asymmetrical peaks in the graph representing water level with respect to time (Fig. 2), a characteristic which was observed in previous hydrogeomorphological studies (Carol et al., 2011).

Groundwater temperature shows a tendency to decrease, with values of 17.4 °C at the beginning of April and 15.1 °C at the beginning of May (Fig. 2a). A temperature increase depending on the tide is recorded at the high tide peaks that generate an increase in groundwater level above 0.15 m (Fig. 2b). Lower increases do not generally show variations in groundwater temperature (Fig. 2c).

Surface water and groundwater salinities increase with depth and the variation between low and high tide depends on whether the fluctuation occurs above or below the regional groundwater discharge level. For instance, measurements obtained at high tide above the groundwater discharge level (18 April, 2011) present a surface water salinity which ranges between the low and high tide peaks from 8645 to 16705 mg/L on the surface and from 17940 to 19435 mg/L at the bottom of the riverbed. Such salinity values correspond to a water column of 0.45 m at low tide and 2.87 m at high tide. In groundwater, a similar behavior can be observed, with an increase in salinity between low and high tide ranging from 6500 to 9980 mg/L on the surface and from 12025 to 14040 mg/L at a depth of 1 m (Table 1). Surface water salinity at a high tide which does not exceed the regional discharge level (10 April, 2011) shows values ranging from 15340 to 10465 mg/L on the surface and from 17225 to 10790 mg/L at the bottom of the riverbed. Such values correspond to a water column of 0.65 m at low tide and 1.95 m at high tide. In these conditions, groundwater salinity decreases as it does in surface water, with values between low and high tide ranging from 13130 to 10595 mg/L on the surface and from 16900 to 11050 mg/L at a depth of 1 m (Table 1).

Such a hydrological dynamics, which is determined by periodic fluctuations in the level, salinity and temperature of the water, is key to the development of the crab population and the plant species of the wetland (i.e., *Spartina alterniflora*, *Spartina densiflora*, *Salicornia ambigua*, *Juncus acutus* and *Zizaniopsis bonariensis*), due to the strong dependence of such species on the tidal flows.

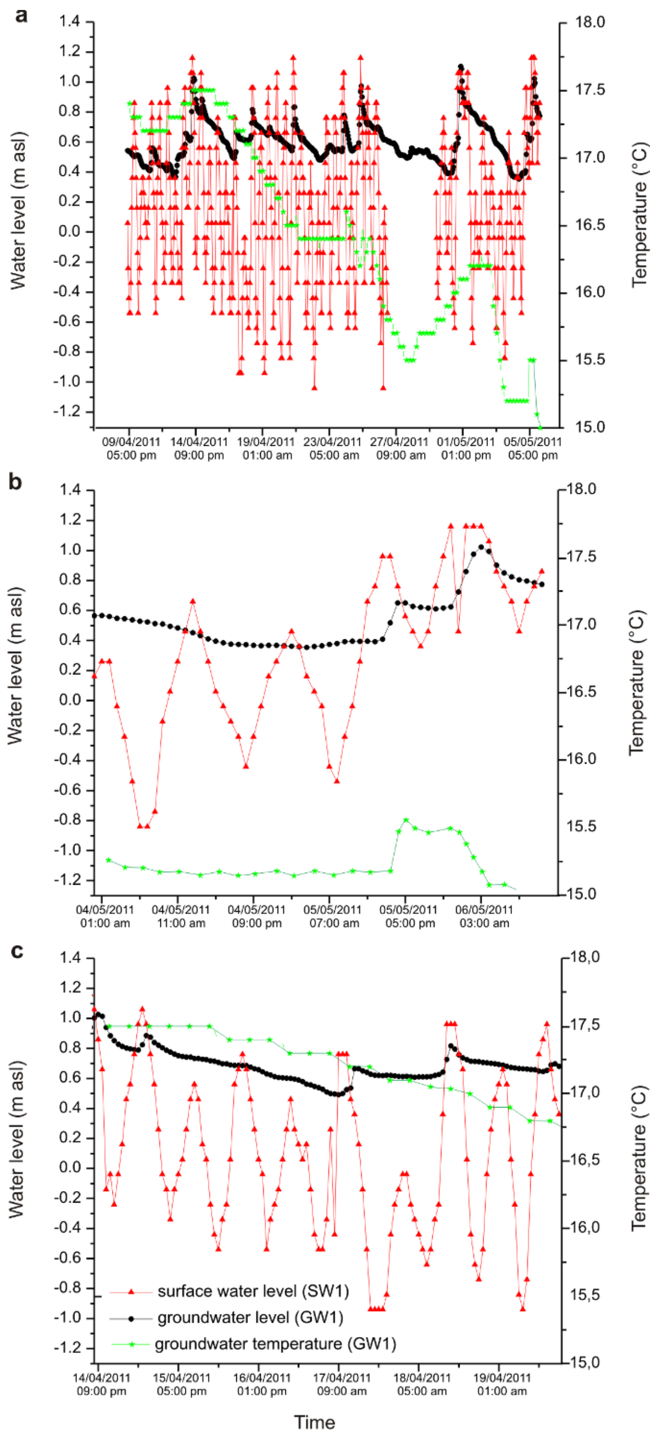

Figure 2. Records of surface and groundwater level and of groundwater temperature in an intertidal marsh area (a) for the period 9 April, 2011–7 May, 2011; (b) detail for the period 4 May, 2011–6 May, 2011; (c) detail for the period 14 April, 2011–19 April, 2011.

Table 1: Salinity values for surface water and groundwater in the natural marsh; LT, low tide; HT, high tide.

Tide exceeding regional mean groundwater discharge level				
	Salinity SW1 (mg/L)		Salinity GW1 (mg/L)	
	surface	bottom of the riverbed	surface	to 1 m depth
LT	8645	17940 (to 0.45 m depth)	6500	12025
HT	16705	19435 (to 2.87 m depth)	9980	14040
Tide below regional mean groundwater discharge level				
	Salinity SW1 (mg/L)		Salinity GW1 (mg/L)	
	surface	bottom of the riverbed	surface	to 1 m depth
LT	15340	17225 (to 0.65 m depth)	13130	16900
HT	10465	10790 (to 1.95 m depth)	10595	11050

Hydrological conditions in areas of the wetland modified by anthropogenic action

In the wetland there are small-scale engineering works (i.e., levees, roads and canals with floodgates) which alter the natural tidal dynamics. The analysis of the satellite images of the year 2010 and of the field surveys shows that 47 % of the marsh is at present excluded from the tidal cycle due to anthropogenic alterations. According to the historical records (e.g., civil drawings, town council reports, etc.), 90 % of the alterations were carried out before 1997, when the area was appointed as a Ramsar site.

The regulation of the tidal flow in order to allow the expansion of livestock farming was undertaken by means of the construction of levees which prevent the tidal inflow towards the areas used for grazing (Fig. 3 a and c).

In the town of General Lavalle, located on the right bank of the River Ajó, a system of levees and land reclamation has also been implemented in order to reconvert low-lying ground and extend the urban area (Fig. 3 b).

Internal farm access roads also alter tidal flows, as they cut through the tidal channels, locally elevate the height of the marsh and have insufficient drainage (Fig. 4). Besides, the contribution of earthy material originating from the collapse of the roads and the sediments supplied by the tidal flow block the drains, which usually become clogged due to lack of maintenance (Fig. 4b).

The channelization with floodgates that regulate the discharge of the Canal 2 and the El Palenque Canal towards the River Ajó affect the southern end of the marsh. In the course of these canals, as they flow into the River Ajó, there are floodgates preventing the inflow of water from the estuary and regulating the flow of the water surplus towards the bay. The floodgates are kept closed in order to allow the flow towards the river only in the case of an emergency, when the rainfall excess floods the area. The floodgate in the El Palenque Canal has a direct impact on the marsh area, preventing tidal inflow from the river and leaving the area upstream out of the tidal cycle (Fig. 5).

In the areas excluded from the tidal cycle due to anthropogenic action, the surface water and groundwater levels do not show variations depending on the tide (Fig. 6). The surface water records mean levels of 0.40 m asl, whereas in groundwater the mean level is 0.50 m asl. The fluctuations recorded are associated to precipitation events, and in the period under study they only represent level variations below 0.20 m. Periodical measurements carried out since 2006 show a direct response of the water levels to precipitation, with an increase in level in the rainy periods and a decrease in the dry periods (Carol, 2008). In this particular case, the precipitation events occurring between 11 and 17 April, which reached a total of 42 mm, caused a slight increase in the water table observed on such dates.

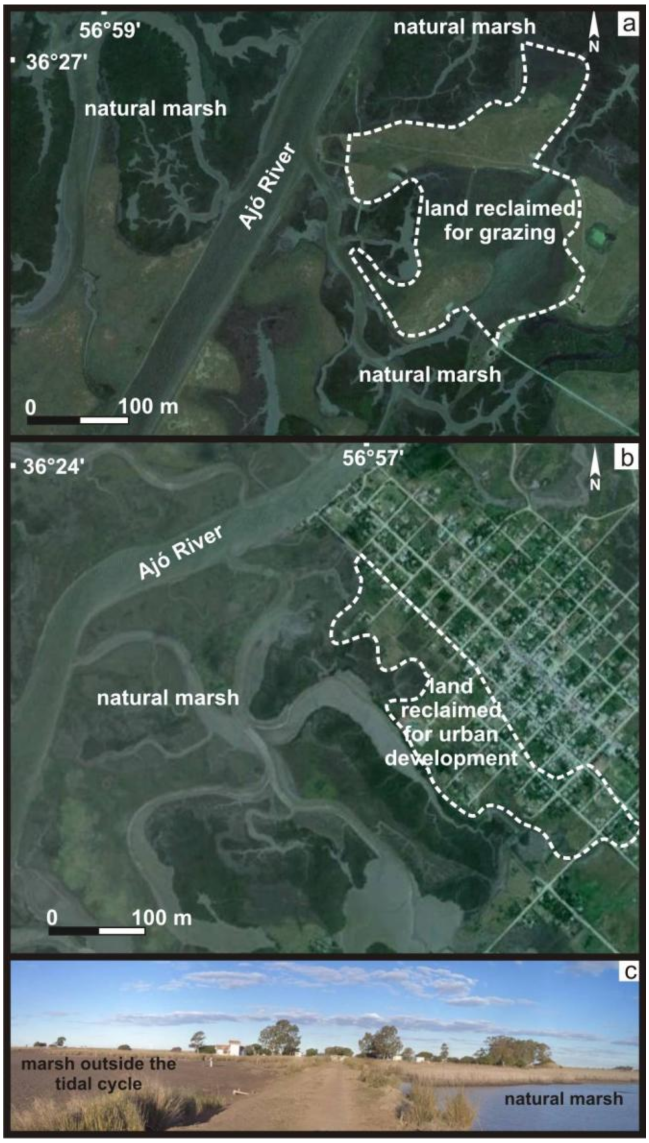

Figure 3. (a) Image of the marsh area with levees to reclaim low-lying ground for grazing; (b) image of the marsh with levees in the urban area to extend constructions; (c) photo of the levee appearing in image (a), in whose centre a levee excluding a section of the marsh from the tidal cycle (to the left of the image) can be observed.

Groundwater–surface water interaction does not undergo alterations, offering evidence of permanent groundwater discharge towards the canal. This characteristic is reflected in the fact that surface water has a lower level than groundwater in all of the level records collected at the SW2 and GW2 sites (Fig. 6).

The temperature of groundwater varies from 17.4 °C at the beginning of April and 15.1 °C at the beginning of May (Fig. 6), a variation which is related to climate seasonality.

Figure 4. (a) Photo of the marsh area in which an internal road lacking drainage blocks the tidal flow towards the marsh section to the right of the image; (b) internal road with blocked drainage pipes; (c) tidal channel intersected by an internal road with no drainage.

Figure 5. (a) Image of the marsh area excluded from the tidal cycle due to the presence of floodgates in the canals; (b) detail of the floodgates

Surface water and groundwater salinities do not vary with depth, recording similar mean values of 5648 mg/L in surface water and 7215 mg/L in groundwater; these values correspond to a water column in the El Palenque Canal of 0.95 m, with measurements carried out at a depth of 1.00 m of water in the aquifer. Such measurements show that during rainfall events, with mean monthly values above 100 mm (February 2012), this value decreases, recording values of up to 1490 mg/L in surface water and 2025 mg/L in groundwater; whereas during dry periods, with mean monthly values below 25 mm (January 2011), an increase in water salinity can be observed, with values reaching 10390 mg/L in surface water and 23600 mg/L in groundwater. In dry periods, it is also common for cracks and saline deposits to develop on the surface of the soils, with a predominance of NaCl-type salts.

This hydrologic alteration conditions the characteristics of the substratum, preventing the development of crab populations and modifying the vegetation. The typical species of the marsh are displaced by species which do not depend on the tidal cycle, such as *Distichlis spicata, Solanum glaucophyllum* and *Cestrum parquii*.

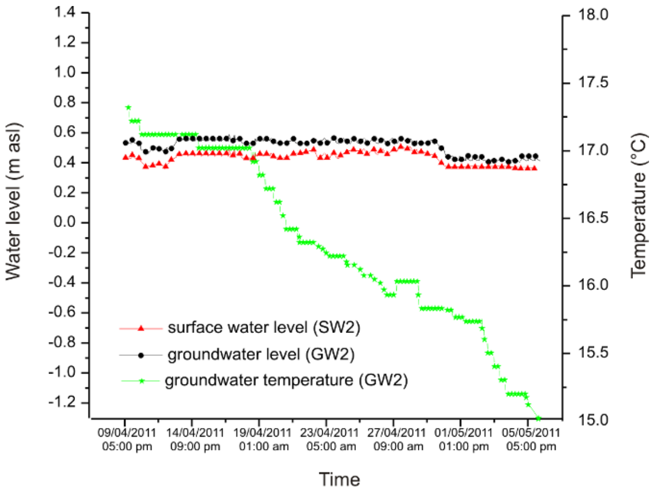

Figure 6. Records of surface and groundwater level and of groundwater temperature in a marsh area excluded from the tidal cycle for the period 9 April, 2012–7 May, 2012

CONCLUDING REMARKS

In natural conditions, the intertidal wetland has a complex hydrological behavior conditioned by the tidal flow. The saline stratification of surface and groundwater is a distinctive characteristic, and the variations in level, salinity and temperature of groundwater depend on their interaction with continental surface water. Estuary water enters the wetland when the high tide exceeds the groundwater discharge level and causes an increase in surface water salinity. The marsh is flooded and the surface water contributes to the water table, causing an increase in the levels and in the salinity and temperature of the groundwater.

If the high tide reaches the groundwater discharge level, there is an accumulation of water in the aquifer which cannot be drained, with the consequent rise in the water tables. When this occurs, the rise in levels is not associated with an increase in salinity or temperature in groundwater.

When the high tide does not exceed the groundwater discharge level, the rise in the water level in the estuary at high tide prevents the discharge of surface water towards the bay. The low-salinity continental drainage water is accumulated in the marsh, causing a decrease in surface water salinity at high tide. The water table and the temperature do not show variations, whereas groundwater salinity decreases, as it does in the surface water. As river water does not enter into the groundwater system, the salinities tend to become similar as a result of chemical equilibrium.

In the marsh areas excluded from the tidal cycle due to anthropogenic action (e.g., construction of roads, levees, canals), the level, salinity and temperature of surface and groundwater are independent from the tidal flow. The surface water–groundwater interaction does not vary, and the salinity in both is homogeneous in the entire water column. Groundwater temperature varies depending on the ambient temperature and the slight variations in level are related to the rainfall pattern.

At present, 47 % of the marsh is excluded from the tidal cycle. This entails a major alteration in the natural ecosystems, exerting a negative influence on the preservation of the environmental characteristics of the wetland

The data collected show how human actions aiming at promoting social and economic development directly affect hydrology and the environment. Besides, they serve as an important precedent to be taken into consideration for the sustainable management of natural resources in the region, which should consider the balance between water and land use and the preservation of the environmental conditions required for the conservation of the wetland.

In the future, civil engineering works should be planned so as to minimize the alteration of water flows. Increasing the number of drains in roads, periodically cleaning the ones already built and regulating the construction of levees will cause the tidal flow in the marsh to be less affected. Guidelines such as the ones described will also make it possible to achieve the sustainable management of natural resources without affecting the social and economic development of the area.

ACKNOWLEDGEMENTS

The authors are very grateful to the Consejo Nacional de Investigaciones Científicas y Técnicas (National Scientific and Technical Research Council), Argentina, for funding this research (PIP 0414/08).

LITERATURE CITED

Acha, M., Mianzan, H., Guerrero, R., Carreto, J., Giberto, D., Montoya, N. and Carignan, M., 2008. An overview of physical and ecological processes in the Río de la Plata Estuary. *Continental Shelf Research* 28, 1579–1588.

Cao, M., Xin, P., Jin, G. and Li, L., 2012. A field study on groundwater dynamics in a salt marsh – Chongming Dongtan wetland. Ecological Engineering 40, 61–69.

Carol, E., 2008. Procesos hidrológicos en el sector sur de la Bahía de Samborombón. PhD Thesis, Universidad Nacional de La Plata, Buenos Aires, Argentina.

Carol, E., Kruse, E. and Pousa, J., 2008. Environmental hydrogeology of the southern sector of the Samborombon bay wetland, Argentina. *Environmental Geology* 54, 95–102.

Carol, E., Kruse, E. and Mas Pla, J., 2009. Hydrochemical and isotopical evidence of ground water salinization processes on the coastal plain of Samborombón Bay, Argentina. *Journal of Hydrology* 365, 335–345.

Carol, E., Kruse, E. and Pousa, J., 2011. Influence of the geologic and geomorphologic characteristics and of crab burrows on the interrelation between surface water and groundwater in an estuarine coastal wetland. *Journal of Hydrology*, 403, 234–241.

Carol, E., Dragani, W., Kruse, E. and Pousa, J. 2012. Surface water and groundwater characteristics in the wetlands of the Ajó River (Argentina). *Continental Shelf Research*.49, 25–33.

Cave, R.R. and Henry, T., 2011. Intertidal and submarine groundwater discharge on the west coast of Ireland. *Estuarine, Coastal and Shelf Science* 92, 415–423.

Chen, X., Flannery, M.S. and Moore, D.L., 2000. Response Times of Salinity in Relation to Changes in Freshwater Inflows in the Lower Hillsborough River, Florida. Estuaries 23, 735–742.

Lenkopane, M., Werner, A., Lockington, D. and Li, L., 2009. Influence of variable salinity conditions in a tidal creek on riparian groundwater flow and salinity dynamics. *Journal of Hydrology* 375, 536–545.

Montalto, F., Steenhuis, T. and Parlange, J., 2006. The hydrology of Piermont Marsh, a reference for tidal marsh restoration in the Hudson river estuary, New York. *Journal of Hydrology* 316, 108–128.

Taniguchi, M., Stieglitz, T. and Ishitobi, T., 2007. Temporal variability of water quality of submarine groundwater discharge in Ubatuba, Brazil. *Estuarine, Coastal and Shelf Science* 76, 484–492.

Vernberg, F.J., 1993. Salt marsh processes: a review. *Environmental Toxicology and Chemistry* 12, 2167–2195.

Xin, P., Yuan, L., Li, L., Barry, D.A., 2011. Tidally driven multiscale pore water flow in a creek-marsh system, *Water Resources Research* DOI:10.1029/2010WR010110.

Yuan, D. and Lin, B., 2009. Modelling coastal ground- and surface-water interactions using an integrated approach. *Hydrological Processes* 23, 2804–2817.