Continental Shelf Research 49 (2012) 25–33

Contents lists available at SciVerse ScienceDirect

Continental Shelf Research

journal homepage: www.elsevier.com/locate/csr

Research papers

Surface water and groundwater characteristics in the wetlands of the Ajó River (Argentina)

E.S. Carol [a],*, W.C. Dragani [b], E.E. Kruse [a], J.L. Pousa [a]

[a] Universidad Nacional de La Plata (UNLP), Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Facultad de Ciencias Naturales y Museo, 64 no. 3, (1900), La Plata, Argentina
[b] Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Argentina

ARTICLE INFO

Article history:
Received 18 May 2012
Received in revised form
24 August 2012
Accepted 17 September 2012
Available online 23 September 2012

Keywords:
Marsh
Surface water
Groundwater
Salt water intrusion

ABSTRACT

Intertidal wetlands are complex hydrological environments in which surface water and groundwater interact periodically with tidal flows. This work analyzes how the tidal flow determines the hydrodynamics and salinity of surface water and groundwater at different depths in the intertidal wetland located in the marsh of the Ajó River. Water level and salinity measurements were obtained from the Ajó River, the channels discharging into the river and the phreatic aquifer. The results in the natural marsh indicate the presence of saline stratification and that the surface water–groundwater relationship varies with the tide. At low tide, the water table discharges into the surface watercourses, and when the high tide rises above the regional groundwater discharge level, the tidal flow contributes to the water table, which causes an increase in salinity in surface water and groundwater. When the high tide does not rise above the discharge level, the tidal flow only enters the groundwater at the mouth section and the salinity of the surface water and groundwater decreases from low tide to high tide. In the marsh areas excluded from the tidal cycle due to the presence of floodgates, the water table always discharges into the canals, and in the surface water and groundwater there is no presence of saline stratification. The results obtained make it possible to generate a conceptual model of hydrological behaviour which shows the hydrodynamic and hydrochemical complexity of intertidal wetlands.

1. Introduction

Intertidal wetlands are complex hydrological systems characterized by strong, dynamic interactions between coastal surface water and groundwater, driven particularly by tides. In these environments, the access of tidal water towards the continent at high tide causes periodic variations in the quality of surface water and groundwater which condition the habitat of its animal and plant communities (Montalto et al., 2006; Werner and Lockington, 2006). This determines a close relationship between the hydrology of wetlands and their capacity to provide ecosystem services (Odum et al., 1995), such as water purification, carbon fixation in vegetation and soils, etc. The hydrodynamic and hydrochemical characteristics of surface water and groundwater in intertidal environments are important as they make it possible to assess the influence of contamination processes in the sediments of tidal channels (Sanger et al., 1999), the response of biological species to human development in this type of habitat (Lerberg et al., 2000; Mallin et al., 2000), the variations in nutrient flow depending on the tides (Guo et al., 2009), currents, salinity and suspended sediments in the intertidal watercourses affected by hydraulic works (Mitchell et al., 2008; Hanes et al., 2011), among others.

The socioeconomic development of intertidal wetlands entails hydrological alterations due to the construction of roads, canals, floodgates, etc. At present, there is a growing interest in the hydrological preservation of this type of wetland, which requires a comprehensive study of the tidal flows in the surface and subsurface components of the hydrological cycle.

The objective of this work is to analyze how the tidal flow determines the hydrodynamics and salinity of surface water and groundwater in the intertidal wetland. In order to do so, the area chosen as case study was the Ajó River area in the southern sector of the Samborombón Bay wetland, located in the outer portion of the Río de la Plata estuary, Argentina (Fig. 1).

In the past few years, there has been a growing interest in the hydrological study of intertidal environments with the development of numerical models to simulate the combined groundwater and surface water flows in coastal areas (Yuan and Lin, 2009), to investigate the influence of estuarine salinity variations on the groundwater flow and salt dynamics in the adjacent aquifer (Lenkopane et al., 2009), to define a soil saturation index of salt

---

* Corresponding author.
E-mail addresses: eleocarol@fcnym.unlp.edu.ar (E.S. Carol), dragani@hidro.gov.ar (W.C. Dragani), kruse@fcnym.unlp.edu.ar (E.E. Kruse), jlp@fcnym.unlp.edu.ar (J.L. Pousa).

0278-4343/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.csr.2012.09.009

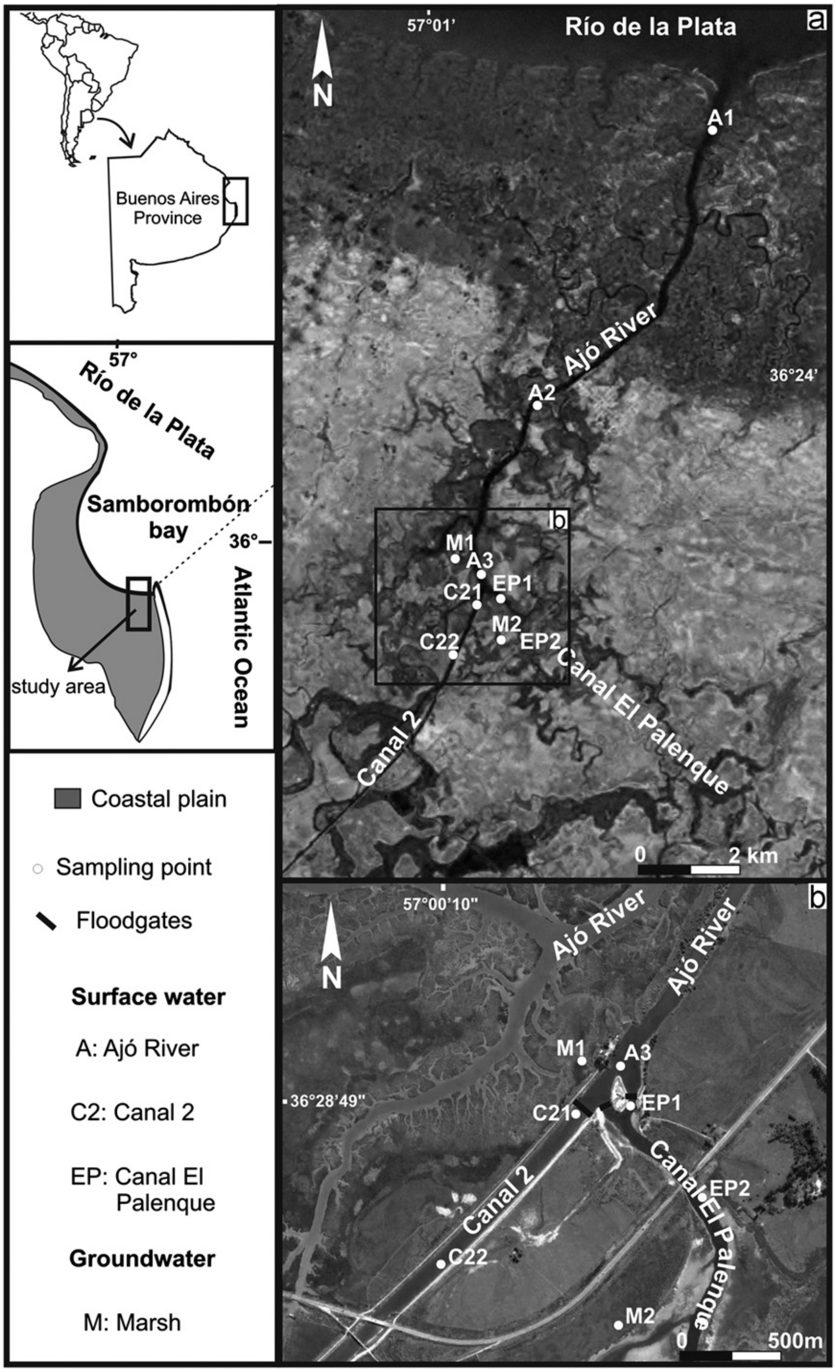

Fig. 1. Location map and sampling points.

marshes (Xin et al., 2010), to examine multiscale pore water flow in a creek-marsh system (Yuan et al., 2011), or to investigate the interactions of surface water and groundwater in a creek-marsh system, with a particular focus on tidally driven pore water flow in marsh soils (Xin et al., 2011). The field studies and conceptual models of hydrological behaviour such as the ones suggested in this work are the basis for the development and calibration of mathematical models.

1.1. Study area

The study area comprises the southern sector of the Samborombón Bay wetland, designated as a RAMSAR site in 1997 (Fig. 1). The climate is sub-humid to humid, with a mean annual precipitation of 970 mm (1887–2011); March is the wettest month (98 mm) whereas June is the driest (67 mm). The mean annual temperature in the region is 14.6 °C; with the highest temperature recorded in January (21.8 °C) and the lowest in July (9.1 °C). As for the actual evapotranspiration rate, it is 770 mm/yr; the largest water surplus in the hydrologic budget occurs during the winter months, although precipitations are low (Carol et al., 2011).

Apart from the ecological importance of the site, which is home to endangered species, there is in this sector a small village with a fishing port which – together with cattle breeding – is the main source of livelihood for the population. As a result of the socio–economic development of the region, different civil engineering projects (e.g., canals, floodgates, roads, etc.) were undertaken in order to maximize surface drainage towards the bay and to limit the spreading of tidal flows towards the continent.

The wetland develops on the coast of the outer estuary of the Río de la Plata, which has a microtidal regime, mainly semidiurnal, with significant diurnal inequalities, in which a wedge-shaped layer of saltwater flows from the sea, penetrating underneath the freshwater from the river (Acha et al., 2008). The Ajó River is the main intertidal watercourse in the area and is connected to a large number of smaller tidal channels. Its main inflowing canals are the Canal El Palenque, which drains the coastal plain area located to the south, and the Canal 2, which carries allochthonous water flowing from a higher area located to the southwest (Fig. 1). Before flowing into the Ajó River, both canals have floodgates which prevent water inflow from the estuary and regulate the flow of the water surplus towards the bay. Since 2008, the floodgate system has been kept closed, allowing the outflow towards the river only in emergency situations when the area is flooded due to rainfall excess. Based on historical records, the average tidal range in the mid-section of the Ajó River (A2 in Fig. 1) is 1.50 m with variations between 0.50 and 2.50 m, which coincide with water levels fluctuating between -1.20 and 1.30 m. During extraordinary high tides or storm events, extreme heights reaching 1.60 m were recorded.

The slope of the marsh and the hydraulic gradient of the tidal channels are on the order of 10^{-4}. Such a characteristic favours the penetration of the tidal wave towards the continent, and it can be observed that the tidal influence on the river and tidal channels reaches a distance of 20 km from the bay coastline. The regulation by means of floodgates of the tidal flow in the river (A3) limits the propagation of the tidal wave towards the canals discharging into the Ajó River, reducing the area of the active marsh. Thus, the areas of the wetland which at present are excluded from the tidal cycle due to waterworks are adjacent to the Canal 2 and the Canal El Palenque.

In the wetland, the water table is at a shallow depth (less than 1 m below ground level) and water is of the sodium–chloride type (Carol et al., 2009). Sediments are mainly silty–clayey with low hydraulic conductivity, and lie over silty–sandy layers. This environment is inhabited by an abundant crab population, whose burrows function as macropores increasing the vertical hydraulic conductivity of sediments and favouring the penetration of the tidal flow into the aquifer (Carol et al., 2011).

2. Methodology

In order to develop a conceptual model of hydrological behaviour that would explain the relationship between surface water–groundwater and water salinity in different areas of the wetland located in the marsh of the Ajó River, a surface water and groundwater monitoring network was developed.

Salinity and water level measurements were carried out on water from the Ajó River, the canals flowing into the river, and the phreatic aquifer located in the marsh (Fig. 1). The wells located in the marsh were drilled with a hand auger up to a depth of 3 m. A slotted 2-inch PVC screen was placed inside every well and backfilled with gravel, and the pipe has a height that prevents water inflow in the event of complete flooding of the marsh at high tide.

Hydrometric and phreatimetric measurements were obtained using manual probes (hourly measurements) and continuous level and atmospheric pressure sensors, specifically Solinst Model 3001 Leveloggers and Barologgers (measurements every 10 min). Every surface and subsurface measurement point was set with respect to the sea level as defined by the Instituto Geográfico Nacional (National Geographic Institute, Argentina) using a Pentax Automatic Level Model AL-240, which has an accuracy of ± 0.02 m.

Water salinity (in PSU) was estimated by measuring electric conductivity with a Solinst Model 107 TLC manual probe with an hourly frequency at 0.50 m depth intervals in the water column of the river (A3), the Canal El Palenque (EP1 and EP2), the Canal 2 (C21 and C22) and the aquifer (M1 and M2) (Fig. 1). The tests were carried out on 22 February, 2011 (syzygy) between low and high tide, with a tidal range of 2.30 m (A3) and a river water level fluctuation between -1.22 and 1.08 m – a situation in which, during the tidal cycle, the tide may exceed the mean discharge level –, and on 10 April, 2011 (quadrature) between low and high tide, with a tidal range of 1.35 m (A3) and a river water level fluctuation between -1.10 and 0.25 m – a situation in which the tide fluctuates below the mean discharge level.

At the peaks of high and low tide, surface water samples were extracted from the Ajó River, in the mouth section (A1), middle section (A2) and upper section (A3) of the river, and in the Canal 2 (C21) and the Canal El Palenque (EP1), and their major ion content was determined. In the water samples, pH, calcium, magnesium, sodium, potassium, chloride, sulfate, carbonate and bicarbonate were measured. Sample collection, preservation, and chemical analyses of the water samples were carried out in accordance with the standard methods proposed by the APHA (American Public Health Association, 1998). Sodium (Na^+) and potassium (K^+) were determined by flame photometry. Hardness as calcium carbonate ($CaCO_3$), calcium (Ca^{2+}), carbonate (CO_3^{2-}), bicarbonate (HCO_3^-) and chloride (Cl^-) were determined by volumetric methods. Magnesium (Mg^{2+}) was calculated on the basis of data on calcium and total hardness, and sulfate (SO_4^{2-}) was measured by nephelometry.

3. Results

The analysis of the data on variations in surface water and groundwater levels associated to the corresponding salinity data was used to develop a conceptual model of hydrological behaviour in different areas of the wetland. The chemical data on major ion composition of surface water was also analyzed.

3.1. Surface water

Salinity measurements carried out in the water column at A3 show different responses depending on the tidal fluctuations and range. Data obtained between low and high tide for a tidal range of 2.30 m and a fluctuation in the water level of the river between -1.22 and 1.08 m indicate an increase in salinity in the entire water column as the water level of the river rises due to tidal inflow (Fig. 2a, Table 1; data for 22 February, 2011). Within the water column the presence of saline stratification can be observed, which is caused by an increase in salinity towards the bottom of the river bed. At low tide, the water column in the river is 0.75 m and the salinity is 7.6 at the surface and 16.9 at the bottom. At high tide, the water column is 3.03 m and the salinity is 15.7 at the surface and 18.5 at the bottom. The hourly records carried out at 0.50 m depth intervals in the water column between low and high tide show that when the water level of the river rises, the salinity increases in the entire water column, maintaining the saline stratification and with the saline gradient decreasing (Table 1 data for 22 February, 2011).

In turn, the data obtained between low and high tide for a tidal range of 1.35 m and a fluctuation in the water level of the river between -1.10 and 0.25 m show a decrease in salinity in the entire water column as the water level of the river rises due to

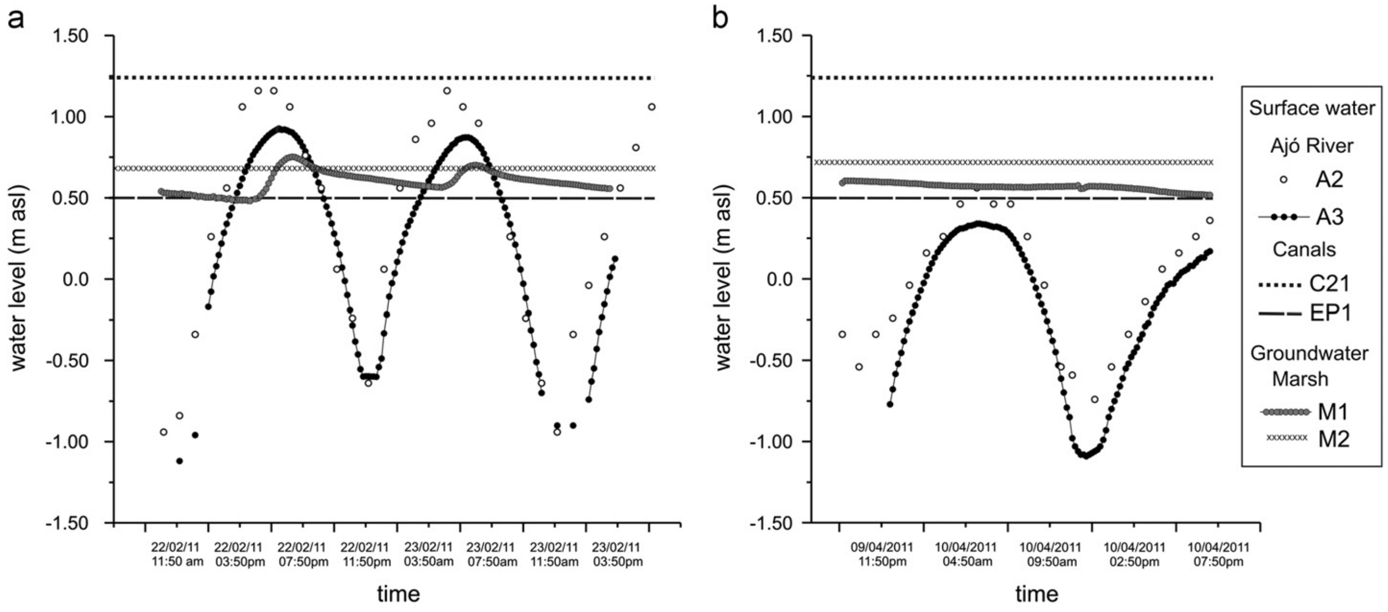

Fig. 2. Variations in surface water and groundwater level as a function of time (a) in periods of tidal fluctuation above the water level of regional discharge (b) in periods of tidal fluctuation below the water level of regional discharge.

Table 1
Values of water level and salinity at different depths in the Ajó River (A3, Fig. 1) from low to high tide on 22 February, 2011 and 10 April, 2011.

22/02/11time (h)	Level m	Salinity of surface water at different depths at A3						
		0.00 m	0.50 m	1.00 m	1.50 m	2.00 m	2.50 m	3.00 m
08:00 am	−1.18	7.6	16.9	–	–	–	–	–
09:00 am	−1.13	11.3	13.2	–	–	–	–	–
10:00 am	−1.22	18.1	14.6	–	–	–	–	–
11:00 am	−0.96	10.7	14.3	16.1	–	–	–	–
12:00	−0.03	13.2	13.8	17.7	17.9	17.9	–	–
01:00 pm	0.34	13.5	16.3	17.7	17.7	17.7	–	–
02:00 pm	0.72	14.5	14.6	17.7	17.7	18.4	18.5	–
03:00 pm	0.85	14.5	15.3	17.7	17.8	18.4	18.5	18.5
04:00 pm	0.96	15.3	15.3	17.5	18.2	18.5	18.5	18.5
05:00 pm	1.00	15.7	15.3	17.4	18.4	18.4	18.5	18.5
06:00 pm	0.98	15.6	15.5	17.5	18.2	18.4	18.5	18.5
07:00 pm	0.62	16.1	16.0	17.6	17.9	18.1	18.1	–
10/04/11time (h)								
08:00 am	−0.98	14.3	16.2	16.2	–	–	–	–
09:00 am	−1.10	12.4	14.1	–	–	–	–	–
10:00 am	−1.07	11.4	13.7	13.5	–	–	–	–
11:00 am	−0.85	11.1	12.4	12.9	–	–	–	–
12:00	−0.54	10.4	19.4	11.6	11.8	–	–	–
01:00 pm	−0.23	10.2	10.7	11.2	11.2	–	–	–
02:00 pm	−0.18	10.1	10.2	10.8	10.9	–	–	–
03:00 pm	0.06	9.6	10.3	10.5	10.4	10.4	–	–
04:00 pm	0.13	9.5	10.2	10.2	10.2	10.2	–	–
05:00 pm	0.22	9.1	9.6	9.7	9.7	9.8	–	–
06:00 pm	0.25	9.4	9.5	9.6	9.6	9.7	–	–

tidal inflow (Fig. 2b, Table 1 data for 10 April, 2011). At low tide, the water column in the river is 0.60 m and the salinity at the surface is 12.4 and at the bottom 14.1. At high tide, the water column is 1.80 m and the salinity is 9.4 at the surface and 9.7 at the bottom. Between low and high tide, the hourly records of water salinity carried out at 0.50 m depth intervals show the stratification of the water column caused by an increase in salinity with depth (Table 1; data for 10 April, 2011). The saline gradient between the surface and the bottom decreases with tidal inflow.

The floodgates located 20 km away from the coastline regulate the intertidal flow of the canals flowing into the river. Even though both gates are closed, there is a small volume of water that may seep in both directions of the flow, depending on the difference in water levels between the river and the canals.

The water level in the Canal El Palenque fluctuates between 0.40 and 0.60 m (Fig. 2) and at the sampled site EP1 it has a depth between 1.30 and 1.50 m. The data obtained on tidal fluctuations above the water level of the canal (Fig. 2a, Table 2; data for 22 February, 2011) show that at low tide water salinity is similar in the entire water column with values of 7.7 on the surface and 7.8 at the bottom of the canal. When the water level of the river is higher than that of the canal and the tidal flow enters the canal, fluctuations in water salinity are registered at the bottom of the

Table 2
Values of water level and salinity at different depths in the Canal El Palenque (EP1, Fig. 1) from low to high tide on 22 February, 2011 and 10 April, 2011.

22/02/11 time (h)	Level m	Salinity of surface water at different depths at EP1		
		0.00 m	0.50 m	1.00 m
08:00 am	0.52	7.7	7.8	7.8
09:00 am	0.52	7.7	7.8	7.8
10:00 am	0.52	7.7	7.8	7.8
11:00 am	0.52	7.7	7.8	7.8
12:00	0.52	7.7	7.8	7.8
01:00 pm	0.52	7.7	7.8	7.8
02:00 pm	0.52	7.8	7.9	10.3
03:00 pm	0.52	7.8	7.9	10.7
04:00 pm	0.52	8.0	8.1	11.3
05:00 pm	0.52	8.0	8.2	11.6
06:00 pm	0.52	8.0	8.1	11.3
07:00 pm	0.52	8.0	8.2	11.4
10/04/11 time (h)				
08:00 am	0.57	7.5	7.5	7.5
09:00 am	0.57	7.5	7.5	7.5
10:00 am	0.57	7.5	7.5	7.5
11:00 am	0.57	7.5	7.5	7.5
12:00	0.52	7.4	7.4	7.5
01:00 pm	0.57	7.4	7.4	7.4
02:00 pm	0.57	7.3	7.4	7.4
03:00 pm	0.57	7.0	7.0	7.0
04:00 pm	0.57	7.0	7.0	7.0
05:00 pm	0.57	6.9	6.9	6.9
06:00 pm	0.57	6.9	7.0	7.0

Table 3
Values of water level and salinity at different depths in the Canal 2 (C21, Fig. 1) from low to high tide on 22 February, 2011 and 10 April, 2011. The final row corresponds to the values of a single measurement obtained after an extraordinary high tide on 27 May, 2011.

22/02/11time (h)	Level m	Salinity of surface water at different depths in C21						
		0.00 m	0.50 m	1.00 m	1.50 m	2.00 m	2.50 m	3.00 m
08:00 am	1.14	2.1	2.1	2.3	2.3	2.4	2.4	2.4
10:00 am	1.14	2.3	2.3	2.3	2.3	2.3	2.3	2.3
12:00	1.14	2.4	2.4	2.4	2.4	2.4	2.4	2.4
02:00 pm	1.14	2.4	2.4	2.4	2.4	2.4	2.4	2.4
04:00 pm	1.14	2.4	2.4	2.4	2.4	2.4	2.4	2.4
06:00 pm	1.14	2.4	2.4	2.4	2.4	2.4	2.4	2.4
10/04/11time (h)	Level m	Salinity of surface water at different depths in C21						
08:00 am	0.88	2.3	2.3	2.3	2.3	2.3	2.3	2.3
10:00 am	0.88	1.9	1.9	1.9	1.9	1.9	1.9	1.9
12:00	0.88	1.9	1.9	1.9	1.9	1.9	1.9	1.9
02:00 pm	0.88	2.4	2.4	2.4	2.4	2.4	2.4	2.4
04:00 pm	0.88	2.4	2.4	2.4	2.4	2.4	2.4	2.4
06:00 pm	0.88	2.4	2.4	2.4	2.4	2.4	2.4	2.4
27/05/11time (h)	Level m	Salinity of surface water at different depths in C21 (after an extraordinary high tide)						
08:00 am	0.95	1.9	1.9	1.9	7.9	11.5	13.6	13.8

water column, where the salinity increases from 7.8 to 10.3, and reaches values of 11.6 at high tide (Table 2; data for 22 February, 2011). In the tidal periods in which the tidal wave fluctuates below the water level of the canal (Fig. 2b, Table 2; data for 10 April, 2011), salinity in the water column diminishes slightly, and values fluctuating between 7.5 and 6.9 can be observed. Measurements carried out 500 m upstream from the gates (EP2) record significantly lower salinity values (around 1.9) than those previously described, and no variations can be observed within the water column.

The water level in the Canal 2 fluctuates between 1.10 and 1.30 m (Fig. 2) and at the sampled site C21 it has a depth between 2.90 and 3.10 m. The water level of the river is only higher than that of the canal during storm events or extraordinary high tides. In situations in which the tide does not exceed the water level of the canal, the salinity in the entire water column is similar, with values between 1.9 and 2.4 (Table 3; data for 22 February, 2011 and 10 April, 2011). Records obtained a day after an extraordinary tidal event, with a high tide of 1.60 m which caused the water level of the river to exceed that of the canal, show that within the water column a sudden increase in water salinity occurs in the deeper sections. At depths between 0 and 1.50 m the salinity is 1.9, increasing with depth from 11.5 at 2 m to 13.8 at 3 m (Table 3; data for 27 May, 2011). When this stratification occurs, it is of local character and limited to the floodgate area, recording 400 m away from this zone (C22) salinities of about 2.1 in the entire water column.

The samples obtained at high and low tide from the uppermost portion of the water column in the Ajó River show that there are spatial variations regarding the ion content. Concentrations of the

Table 4
Hydrochemical data on surface water (in mg/L).

Sample	pH	Cl^-	HCO_3^-	SO_4^{2-}	NO_3^-	Ca^{2+}	Mg^{2+}	Na^+	K^+
A1 ht	8.1	6909	182	1040	110	196	410	3845	95
A1 lt	7.8	7273	272	1184	120	222	432	4100	89
A2 ht	8.1	6182	151	1040	75	178	367	3410	65
A2 lt	7.8	6273	303	1040	110	222	416	3675	88
A3 ht	8.1	4318	338	752	122	240	227	2670	112
A3 lt	8.2	4818	326	896	108	213	303	2730	144
EP1 ht	7.8	1585	341	440	9	80	165	950	65
EP1 lt	7.9	1590	366	428	12	88	163	980	59
C21 ht	7.9	405	262	237	4	116	41	340	25
C21 lt	8.0	420	270	248	4	120	45	330	25

Table 5
Values of water level of the phreatic aquifer at the marsh (M1, Fig. 1), and salinity at different depths from low to high tide on 22 February, 2011 and 10 April, 2011.

22/02/11time (h)	Level m	Salinity of groundwater at different depths at M1		
		0.00 m	0.50 m	1.00 m
08:00 am	0.53	5.6	10.9	–
09:00 am	0.53	5.7	11.6	–
10:00 am	0.53	6.5	12.4	–
11:00 am	0.52	7.2	14.4	–
12:00	0.50	7.9	15.0	–
01:00 pm	0.49	8.3	14.7	–
02:00 pm	0.48	8.6	14.1	–
03:00 pm	0.50	8.8	15.3	–
04:00 pm	0.65	8.4	13.2	15.4
05:00 pm	0.74	8.7	12.6	15.6
06:00 pm	0.73	8.8	12.9	15.6
07:00 pm	0.74	9.1	13.2	15.7
10/04/11time (h)				
08:00 am	0.57	12.0	15.9	–
09:00 am	0.57	12.7	15.5	–
10:00 am	0.57	13.6	14.9	–
11:00 am	0.57	13.1	13.8	–
12:00	0.57	11.8	12.4	–
01:00 pm	0.57	11.1	11.8	–
02:00 pm	0.57	10.9	11.4	–
03:00 pm	0.57	10.1	10.5	–
04:00 pm	0.57	10.1	10.2	–
05:00 pm	0.57	9.7	10.0	–
06:00 pm	0.57	9.5	10.0	–

Cl^-, Na^+, SO_4^{2-} and Mg^{2+} ions, which are the most abundant in seawater (Hem, 1985), increase from the upper section (A3) towards the mouth section (A1), and their concentration is higher at high tide than at low tide. In turn, the predominant ions in continental water (HCO_3^- and Ca^{2+}) have an inverse gradient, with the highest concentrations at the upper section (A3) and the lowest at the mouth section (A1), whereas K^+ and NO_3^- do not show significant spatial variations (Table 4).

In the area near the floodgates on the Canal 2 and the Canal El Palenque (C21 and EP1), the concentrations of all major ions are lower than those in the river, except for HCO_3^- at EP1, which shows a similar value to the one in the river at the upper section (A3). Such a similitude in HCO_3^- content, which is typical of continental water discharge, is due to the fact that the Canal El Palenque is the main tributary of the river at the upper section.

Water in both canals is chemically different from the one in the intertidal area, and the concentrations of all analyzed ions at high and low tide are similar.

3.2. Groundwater

In the marsh (M1), the relationship between the levels of surface water and groundwater varies depending on the fluctuation level of the tidal wave in the river. The relationship between the water levels in the river and in the aquifer shows that in situations in which during the cycle the tide exceeds the water table (Fig. 2a), at low tide the groundwater flow discharges into the tidal channels and the river, whereas at high tide the flow is from the surface watercourses towards the aquifer. The access of the tidal flow towards the aquifer occurs when the marsh is flooded at high tide, and it can be observed that there is a sudden rise in water level when the high tide exceeds the water table. When the tidal wave fluctuates below the level of the water table, no fluctuations in the water table of the aquifer can be observed (Fig. 2b).

As in the case of the river, salinity measurements carried out between 0 and 0.50, and/or 1.00 m below the water table in the marsh adjacent to A3 show that the behaviour changes depending on the tidal range and the fluctuation level. In the case in which a tidal range of 2.30 m was recorded in the river, with a fluctuation between −1.22 and 1.08 m, an increase in salinity in the water column analyzed could be observed (Table 5; data for 22 February, 2011). At low tide, the water at the uppermost section of the aquifer has a salinity of 5.6, whereas at a depth of 0.50 m it rises to 10.9. At high tide, these values increase to 9.1 at the uppermost section, 13.2 at a depth of 0.50 m and 15.7 at a depth of 1.00 m. Such saline stratification can be observed in all the measurements carried out between low and high tide (Table 5; data for 22 February, 2011).

At the same sampling point (M1), when the tide has a range of 1.35 m and fluctuates between −1.10 and 0.25 m, the water in the aquifer, as in the river, shows stratification; and there is a decrease in salinity in the entire water column as the tide flows in (Table 5; data for 10 April, 2011). At low tide, the salinity of groundwater is 12.0 at the uppermost section and 15.9 at a depth of 0.50 m. At high tide, these values decrease to 9.5 at the surface and 10.0 at a depth of 0.50 m. This saline stratification and decrease in salinity can be observed in all the hourly records obtained between low and high tide (Table 5; data for 10 April, 2011).

The levels recorded in the marsh area which is at present excluded from the tidal cycle (M2) do not show variations with the tide (Fig. 2). The salinity in these sectors of the marsh does not vary with the tidal period and its mean value is 4.3 in the proximity of the floodgates and 2.0 upstream from the gates.

3.3. Conceptual model

The hydrodynamic and hydrochemical characteristics of surface water and groundwater in the intertidal area of the wetland (i.e., the marsh extending from the coastline to the floodgate area) vary depending on the tidal range and fluctuation level, and two situations can be identified.

In the first case, when the tidal wave has a range which exceeds the average range (>1.50 m) and fluctuates above the discharge level of the river at the upper course, an inversion of the flow is registered at high tide with higher water levels at the river mouth than at the upper section (Fig. 3a_2 and a_4). Under these conditions the estuary water flows towards the upper course of the river, flooding the marsh. As the estuary water has a higher salinity, and is therefore denser, it enters along the bed of the river as a wedge-shaped layer. In such cases, stratification with an increase in salinity can be observed in the entire water column at high tide (mouth section, Fig. 3a_1 and a_2; upper section, Fig. 3a_3 and a_4). The access of the tidal flow towards the aquifer occurs when the marsh is flooded at high tide and water infiltrates vertically through the macropores of the crab burrows, causing a sudden rise in the water table. 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. This sub-horizontal groundwater flow is conditioned by the low permeability of the silty sediments of the marsh, and not by

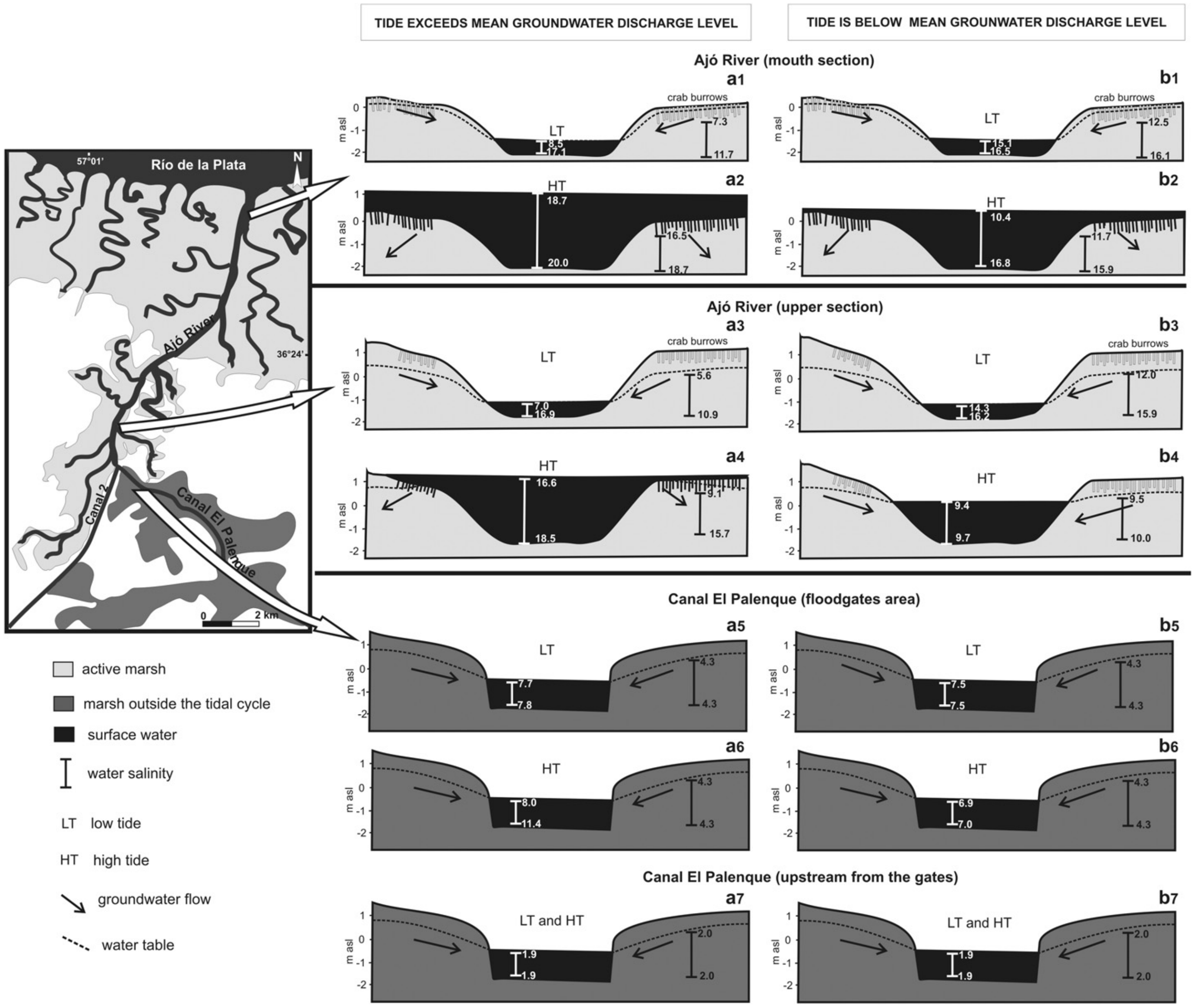

Fig. 3. Conceptual model of hydrological behaviour.

the macropores of the crab burrows. That is why the transference of groundwater towards the river is very slow at low tide. This characteristic becomes evident in the presence of asymmetrical peaks in the graph showing the water level with respect to time (Fig. 2a). This access of the tidal flow produces in the groundwater of the marsh an increase in the salinity of the entire water column, which is associated to stratification similar to the saline wedge observed in the river (mouth section, Fig. 3a$_1$ and a$_2$; upper section, Fig. 3a$_3$ and a$_4$).

In the second case, when the tidal wave has a range below the mean range (<1.50 m) and fluctuates below the discharge level of the river at the upper course, the increase in the water level at the river mouth prevents the discharge of the river into the estuary. As it cannot flow outwards, the river water accumulates in the river bed and the marsh, as the high tide causes the discharge level at the mouth section to rise (Fig. 3b$_2$ and b$_4$). Because the continental water flowing into the river has a lower salinity than that of the estuary, a decrease in salinity in the entire water column is registered from low to high tide (mouth section, Fig. 3b$_1$ and b$_2$; upper section, Fig. 3b$_3$ and b$_4$).

At the mouth section, the height of the marsh is below 1 m asl and it is flooded due to the increase in level at high tide, causing the inflow of surface water towards the water level (Fig. 3b$_2$). This does not occur in the upper section, where groundwater discharges into the river even at high tide (Fig. 3b$_4$). The salinity of the phreatic water accompanies the tendency observed in the river, registering a decrease in the salinity of the entire water column at high tide with similar values to the ones recorded in the river. At the mouth section, the decrease in salinity is associated to mixing processes occurring due to an inflow of surface water into the water table; whereas at the upper section, the salinities of the river and of groundwater tend to become similar due to processes of chemical equilibrium.

Major ion concentrations also show the time and space chemical variations that periodically affect the marsh area. At high tide, a saline wedge of estuary water penetrates along the bottom of the river bed and the tidal channels, and its range depends on the tidal fluctuation level. As the level increases at the mouth at high tide, the low salinity water discharged into the river cannot be drained towards the bay, and it accumulates on the surface, mainly at the upper section. As the water level decreases in the estuary at low tide, the continental water accumulated on the surface flows towards the bay, with the water from the estuary remaining at the bottom of the bed. These processes are evident in the chemistry of the surface water of the river, which shows lower ion contents (mainly Cl^-, Na^+ and SO_4^{2-}) at high tide than at low tide.

In the marsh area excluded from the tidal cycle due to channelizations and the presence of floodgates, the surface water–groundwater relationship is unaltered and water salinity follows the tendency to increase or decrease recorded in the river only in the area near the floodgates (Fig. 3a_5, a_6, b_5 and b_6). In the areas located upstream from the floodgates, surface water and groundwater do not reflect variations in level or salinity (Fig. 3a_7 and b_7).

4. Discussion

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

Even though there are other field studies on the variations in water level and/or salinity in coastal environments, these are oriented towards the analysis of data on surface water or groundwater instead of the analysis of the interaction between them. For instance, studies on surface water were carried out by Chen et al. (2000), who modelled on the basis of field data the variations in surface water salinity caused by the influence of changes in freshwater inflow in the Lower Hillsborough River, Florida; by Blanton et al. (2000), who studied the tidal circulation and salinity regime of a coastal plain estuary in Portugal; or by Rockwell Geyer et al. (2008), who evaluated the effects of turbulence on the mixing processes in estuaries. In other cases, the dynamics and quality of groundwater were studied, such as the analysis of groundwater discharge into intertidal areas carried out by Cave and Henry (2011) on the west coast of Ireland; the study on temporal variability of groundwater quality in submarine discharge by Taniguchi et al. (2007) in Ubatuba, Brazil; or the field research undertaken by Cao et al. (2012), who identify the important role that subsurface hydrology plays in the behaviour of a salt marsh, in particular concerning nutrient exchange, plant zonation and carbon cycling in the Chongming Dongtan wetland (China).

In this work, field data are presented in order to assess surface water–groundwater interaction in different areas of an intertidal wetland, and also to analyze the changes occurring in the salinity of the water column, both in the river and the groundwater. In the case study it can be observed how the range and fluctuation level of the tidal wave condition the access of the tidal flow, the surface water–groundwater relationship and the salinity, registering both increases and decreases at high tide.

Surface water–groundwater interaction in intertidal areas has a direct influence on the development of the ecosystems and on the assessment of the impact that land use has on wetlands. The management of water resources associated to the socio–economic development of these regions must implement management guidelines that would minimize the alteration of the hydrodynamic and hydrochemical characteristics, as these are vital to the hydrological and biological functioning of intertidal wetlands.

5. Conclusions

The Ajó River marsh is an intertidal wetland in which surface water–groundwater interaction shows complex variations depending on the fluctuation level of the tide in the estuary with respect to the level of the regional groundwater discharge, on the different sections of the river and on the anthropogenic regulation of tidal flow. The study of salinity and level fluctuations made it possible to recognize differences in hydrological behaviour in the different areas of the marsh.

In the wetland area with no anthropogenic modifications, which extends between the coastline and the floodgates located in the upper section of the Ajó River, the salinity and hydrological dynamics are determined by the tidal flow. In this intertidal area, both in surface water and groundwater, there is saline stratification that fluctuates periodically with the tidal flow.

In the wetland areas which are left out of the tidal cycle due to the presence of floodgates, surface water and groundwater do not show saline stratification and the level remains constant. The tidal flow only penetrates during extraordinary high tides or storms, and its influence is only local.

The results obtained make it possible to generate a conceptual model of hydrological behaviour which shows the hydrodynamic and hydrochemical complexity that intertidal wetlands are periodically exposed to, and how they may be affected by anthropogenic actions.

References

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

APHA, 1998. Standard Methods for the Examination of Water and Wastewater American Water Works Association, Water Environment Federation, twenth ed.. American Public Health Association, Washington, DC, American Public Health Association.

Blanton, J.O., Ferreira, M.A., Andrade, F.A., 2000. Effect of a broad shallow sill on tidal circulation and salt transport in the entrance to a coastal plain estuary (Mira Vila Nova de Milfontes, Portugal). Estuaries 23, 293–304.

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

Carol, E., Kruse, E., 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., 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.

Cave, R.R., 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., 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.

Guo, H., Noormets, A., Zhao, B., Chen, J., Sun, G., Gu, Y., Li, B., Chen, J., 2009. Tidal effects on net ecosystem exchange of carbon in an estuarine wetland. Agricultural and Forest Meteorology 149, 1820–1828.

Hanes, D., Ward, K., Erikson, L., 2011. Waves and tides responsible for the intermittent closure of the entrance of a small, sheltered tidal wetland at San Francisco, CA. Continental Shelf Research 31, 1682–1687.

Hem, J.D., 1985. Study and Interpretation of the Chemical Characteristics of Natural Water. US Geological Survey Water Supply Paper 2254, 263 pp.

Lenkopane, M., Werner, A., Lockington, D., 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.

Lerberg, S.B., Holland, A.F., Sanger, D.M., 2000. Responses of tidal creek macrobenthic communities to the effects of watershed development. Estuaries 23, 838–853.

Mallin, M.A., Williams, K.E., Esham, E.C., Lowe, R.P., 2000. Effect of human development on bacteriological water quality in coastal watersheds. Ecological Applications 10, 1047–1056.

Mitchell, S.B., Burgess, H.M., Pope, D.J., Theodoridou, A., 2008. Field studies of velocity, salinity and suspended solids concentration in a shallow tidal channel near tidal flap gates. Estuarine, Coastal and Shelf Science 78, 385–395.

Montalto, F., Steenhuis, T., 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.

Odum, W.E., Odum, E.P., Odum, H.T., 1995. Nature's pulsing paradigm. Estuaries 18, 547–555.

Rockwell Geyer, R.W., Scully, M.E., Ralston, D.K., 2008. Quantifying vertical mixing in estuaries. Environmental Fluid Mechanics 8, 495–509.

Sanger, D.M., Holland, A.F., Scott, G.I., 1999. Tidal creek and salt marsh sediments in South Carolina coastal estuaries: I. Distribution of trace metals. Archives of Environmental Contamination and Toxicology 37, 445–457.

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

Werner, A., Lockington, D., 2006. Tidal impacts on riparian salinities near estuaries. Journal of Hydrology 328, 511–522.

Xin, P., Gibbes, B., Li, L., Song, Z., Lockington, D., 2010. Soil saturation index of salt marshes subjected to spring-neap tides: a new variable for describing marsh soil aeration condition. Hydrological Processes 24, 2564–2577.

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

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

Yuan, L.R., Xin, P., Kong, J., Li, L., Lockington, D., 2011. A coupled model for simulating surface water and groundwater interactions in coastal wetlands. Hydrological Processes 25, 3533–3546.