Journal of Hydrology 403 (2011) 234–241

Contents lists available at ScienceDirect

Journal of Hydrology

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

Influence of the geologic and geomorphologic characteristics and of crab burrows on the interrelation between surface water and groundwater in an estuarine coastal wetland

Eleonora S. Carol, Eduardo E. Kruse *, Jorge L. Pousa

Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Facultad de Ciencias Naturales y Museo, Universidad Nacional de La Plata (UNLP), Calle 60 y 122, (1900) La Plata, Argentina

ARTICLE INFO

Article history:
Received 27 May 2010
Received in revised form 9 January 2011
Accepted 3 April 2011
Available online 8 April 2011

This manuscript was handled by P. Baveye, Editor-in-Chief

Keywords:
Marshes
Groundwater
Streams
Tides
Samborombon Bay
Argentina

SUMMARY

The interrelation between surface water and groundwater in intertidal flats is often studied through mathematical models. In many cases these models need to be supported by an integral analysis of the geologic, geomorphologic, hydrologic and biological characteristics of the environment that are to be obtained from field surveys. The marshy environment of the River Ajo in the Samborombon Bay wetland, Argentina, is a typical example of an estuarine coastal zone. Geologic and geomorphologic surveys were carried out, as well as measurements of surface water and groundwater level changes as a response of the aquifer to tidal forcing. The banks of the River Ajo are either scarped with storm flats, or mildly sloped with intertidal flats and numerous crab burrows. Sediments are mainly silty-clayey with low permeability, and lie over silty-sandy layers. At the erosion scarps the tidal wave enters the aquifer as a sub-horizontal flow through the pore space of the sediments. The tidal range in the aquifer depends on the lithological characteristics of the sediments and on the side changes of their hydraulic conductivity. The rise of the water table at high water and its subsequent fall are nearly sinusoidal, with a period similar to that of the tide at the river. At the intertidal flats, instead, the tidal wave enters the aquifer mainly as a sub-vertical flow through the crab burrows. As the crab burrows are not interconnected, they are not distinct pathways for preferential flow. Therefore, the groundwater flux into the river is very slow during low water, and the recovery of the water table takes a long time. The tidal influence upon the water table on both kinds of banks affects only a narrow strip of the aquifer. Not only are the characteristics of the marshy environment of the River Ajo representative of most of the Samborombon Bay wetland; they can also be extended to other similar coastal wetlands to help preserve these invaluable environments.

1. Introduction

Estuarine coastal wetlands are transition zones between estuaries and their hinterlands that play a significant role in the exchange of sediments, nutrients, organic matter and solutes between aquatic and land ecosystems. There is a close relationship between the hydrology of wetlands and their capacity to provide ecosystem services (Odum et al., 1995). In a wetland, the physicochemical characteristics of the substratum depend on the periodic fluctuation of surface water and groundwater levels, particularly on those driven by tidal oscillations, which determine the habitat of plant and animal populations (Montalto et al., 2006).

The social and economic development of coastal zones, together with the preservation of the environment, requires a detailed knowledge of the hydrological conditions of the area to evaluate and predict its behavior in view of the changes due to human activities. Anthropic actions can modify the interrelationship between surface water and groundwater in wetlands, thus affecting nutrient dynamics, organic matter decomposition rates, water salinity and redox potential of the substratum, among other processes (Qualls and Richardson, 2000; Bradley, 2002; Holden, 2005; Richardson et al., 2005; Sutula et al., 2001; Iggy Litaor et al., 2008).

The interrelationship between surface water and groundwater in wetlands and tide-dominated coastal zones is usually studied through analytic and numerical models (Nielsen, 1990; Ateie-Ashtiami et al., 1999; Gardner, 2005, 2007; Langevin et al., 2005; Zhiyao et al., 2007; Vandenbohede and Lebbe, 2007; Mulligan et al., 2007; Hailong et al., 2008), but general hydrological works on intertidal wetlands produced by partially or totally collecting and integrating geological, geomorphological, hydrological and biological data are scarce (Genereux and Slater, 1999; Montalto et al., 2006).

* Corresponding author.
E-mail addresses: eleocarol@fcnym.unlp.edu.ar (E.S. Carol), kruse@fcaglp.unlp.edu.ar (E.E. Kruse), jlp@fcnym.unlp.edu.ar (J.L. Pousa).

0022-1694/$ - see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.jhydrol.2011.04.007

Holocene transgression–regression cycles gave rise to coastal plains and marshes that can now be found along the world coastlines in the form of intertidal wetlands (Woodroffe and Davies, 2009). The marsh environment of the River Ajo in the Samborombon Bay wetland in the Province of Buenos Aires, Argentina, is a suitable example of a typical estuarine coastal swamp. The Samborombon Bay wetland extends along 180 km on the west margin of the Rio de la Plata estuary, from Punta Piedras to Punta Rasa (Fig. 1). This wetland covers a strip of land of between 2 and 23 km in width, and a shallow water portion up to the 3.5 m contour line where the waters from runoff, from the Rio de la Plata estuary and from the Atlantic Ocean mix. The Samborombon Bay wetland is an area where migratory birds feed, rest and breed, as well as a reserve for species in danger of extinction (e.g., Ozotocerus bezoarticus celer). Because of these ecological features it was appointed as a Ramsar site in 1997, and is considered a priority area for biodiversity conservation. Dense populations of crabs give the intertidal flat landscape a particular physiognomy locally known as '*cangrejales*' (César et al., 2005), which is a land filled with crabs.

Knowledge of the hydrologic processes in wetlands, particularly of the interrelation between surface water and groundwater, is critical for managing water resources and land use, preserving the ecological features of these invaluable environments as much as possible.

This work aims at taking the swamp of the River Ajo as an example to assess the influence of the geological and geomorphological characteristics of the surrounding environment and of crab burrows on the relationship between surface water and groundwater in this type of estuarine coastal wetland.

2. Study area

2.1. Geological features

The marsh environment of the River Ajo is part of a large coastal plain that developed during the Holocene, simultaneously with a northward migration of a sandy spit from Punta Medanos towards Punta Rasa driven by the Holocene transgression (Fig. 1). Behind this spit, and landwards, a large marsh developed and also migrated northwards, generating the coastal plain (Fig. 1) (Violante et al., 2001). During the evolution of the coastal plain, the tidal channels that lay far away from the coast remained out of the tidal cycle and became depressed paleoforms where water accumulated on the surface. Today, only a coastal strip of the plain, ranging between 1 and 15 km, has tidal channels that are active with respect to the present tidal cycle.

The average altitude of the area is 1.6 m above mean sea level (MSL), with a regional slope of 10^{-4} towards the bay. The surface sediments are composed of clayey silts associated with marine environments, interbedded with shelly and sandy layers (Parker, 1979). Sand sheets of aeolian origin overlie the coastal plain sediments. These sheets are over-elevated geoforms a small area with average heights of 2.5 m above MSL.

2.2. Hydrological features

The climate of the region is sub-humid to humid, with a mean annual precipitation of 930 mm for the period 1887–2007; March (91 mm) and June (67 mm) being the wettest and driest months respectively. The mean annual temperature is 14.6 °C; with the

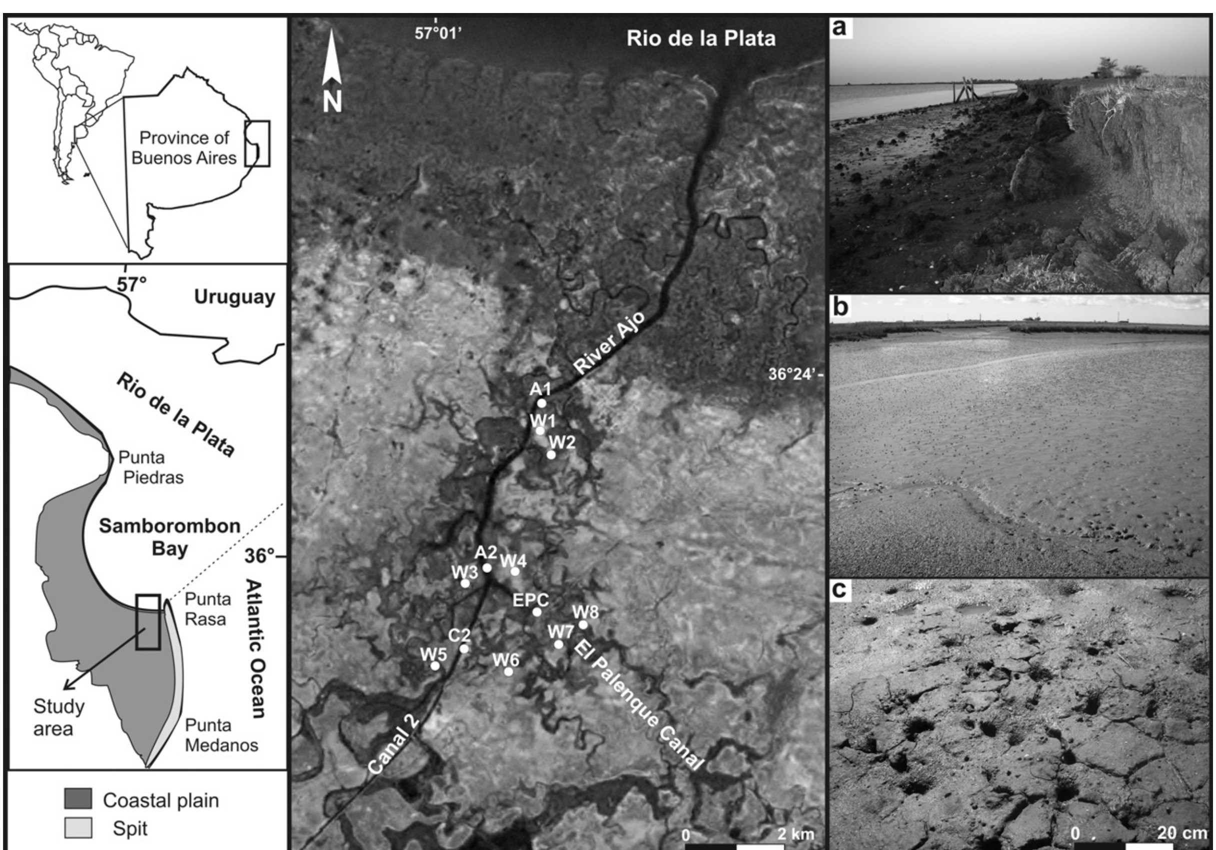

Fig. 1. Left: Location map. Middle: Satellite view of the River Ajo with sampling points: A1–A2; W1–W8; EPC and C2. Right: (a) a scarped bank of the River Ajo; (b) an intertidal flat of the River Ajo with crab burrows; (c) a detailed view showing size and density of crab burrows.

maximum in January (21.8 °C) and the minimum in July (9.1 °C). The actual evapotranspiration rate reaches 770 mm/yr, with the largest water surplus in the hydrologic budget occurring in the winter months, in spite of the low precipitations.

Tides are mixed, predominantly semidiurnal, with a range below 2 m. The average salinity of the southern waters of the Samborombon Bay is 14 g/L (Guerrero et al., 1997). Water surplus in the hydrologic budget is drained by the River Ajo towards the bay. The main contributions come from the El Palenque Canal, which drains the southernmost sector of the coastal plain, and the Canal 2, which carries allochthonous waters from a higher area located to the southwest (Fig. 1). Before flowing into the River Ajo, both canals have gates that prevent the estuary waters from going inland, and control the drainage of the water surplus towards the bay. The surface water of both canals is of Na-Cl type, with salinities ranging between 575 and 1345 mg/L in the Canal 2, and between 1495 and 7080 mg/L in the El Palenque Canal. Water in the River Ajo is also of the Na-Cl type, with salinities that change considerably depending on the prevailing contributions from the Canal 2, El Palenque Canal and the Rio de la Plata (Carol et al., 2009a).

There is a shallow saline aquifer in the coastal plain with a salinity of up to 30 g/L; such a high level is due to the dissolving processes of sediment salts (Carol et al., 2009a).

The sandy sheets in the area are geoforms with distinct geohydrological features, in which low salinity water (between 600 and 1300 mg/L)) from precipitation is stored under the form of lenses lying on the saline groundwater of the coastal plain (Carol et al., 2008).

2.3. The River Ajo

The main course of the River Ajo has a variable width between 500 m at the outlet and 100 m at the head; with a depth ranging from 3 to 6 m. Two different morphologies can be identified at its banks, namely storm flats and intertidal flats. Storm flats are located on topographically higher areas (1.70 m over MSL) and are flooded only during storm events. The corresponding river banks have erosion scarps with heights between 0.4 and 0.6 m (Fig. 1). The surface sediments that make up the aquifer exhibit horizontal lithological variations landwards from the river banks. Close to the river banks, sediments are basically silty-clayey with a horizontal hydraulic conductivity (K) on the order of 10^{-1} m/day; landwards, they become increasingly silty with shell and sand intercalations and a horizontal hydraulic conductivity on the order of 10^2 m/day (Carol et al., 2009b). Intertidal flats, on the other hand, develop in sectors with low topographic heights (between 1.1 and 1.3 m over MSL) and a mild slope, and are partially or entirely flooded by normal high waters (Fig. 1). Sediments are mainly silty-clayey with low permeability, and lie over silty-sandy layers. These features are common to intertidal environments, and can be seen in most marshes (Dolphin et al., 1995; Hughes et al., 1998; Gardner and Porter, 2001; Perillo et al., 2005). Numerous crab populations develop there (Fig. 1). In the study area the holes dug by the crabs are 5–9 cm in diameter and up to 70 cm deep. These macro pores are unevenly distributed over the intertidal flat, with a density between 20 and 50 holes per square meter.

3. Materials and methods

The geology and geomorphology of the study area was analyzed by means of topographic maps, satellite images, aerial photographs and field surveys. A monitoring network of surface water and groundwater was devised with water level measurement points and monitoring wells to study the regional behavior of the water table. The wells were drilled with a hand auger up to a depth of 2.5 m. A slotted, 2-in. PVC screen was placed inside every well and backfilled with gravel.

The influence of the tide on the relationship between surface water and groundwater near the river banks was determined on the basis of hourly water levels recorded by the Prefectura Naval Argentina (Argentine Naval Coastguard) at site A1 (Fig. 1) (River Ajo) for the year 2008 (Fig. 2), and from simultaneous water level measurements along several tidal cycles at sites A1 and A2 (River Ajo), Canal 2 (C2) and El Palenque Canal (EPC) for the period 2–4 August 2008 (Figs. 1 and 3); at sites A1 and W1 (storm flat) for the period 17–19 November 2008 (Figs. 1 and 5), and at sites A2, W3 and W5 (intertidal flats) for the period 1–4 August 2008 (Figs. 1 and 6). At this point, Figs. 3, 5 and 6 are mentioned only to illustrate the shape of the tidal curve at the sites mentioned above; they will be explained below.

Water level measurements were performed with manual probes and with level and atmospheric pressure continuous record sensors of the type Leveloggers and Barologgers, model 3001 Solinst. Every surface water and groundwater measurement site was leveled with respect to MSL as defined by the Instituto Geográfico Militar (Military Geographical Institute) with an Automatic Pentax Level Model AL-240 to an accuracy of ±2.0 mm.

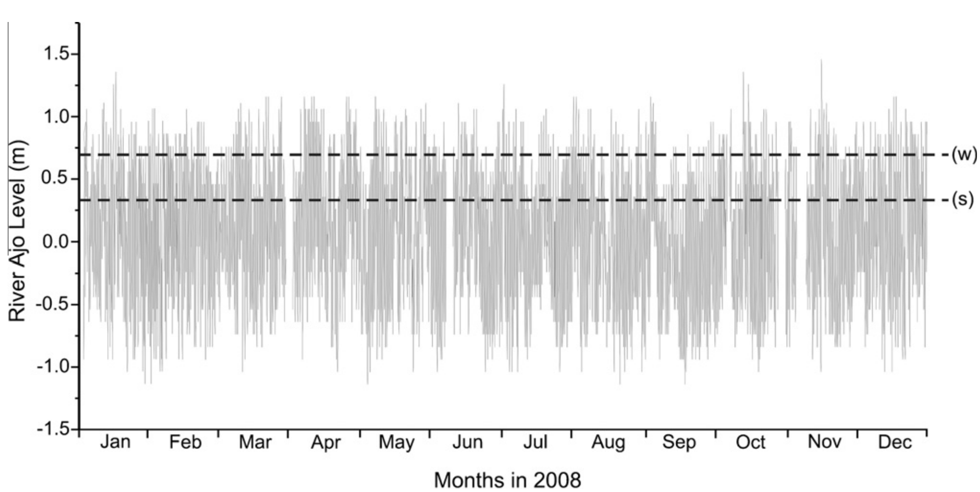

Fig. 2. Hourly water levels for 2008 at site A1 (Fig. 1) from the Prefectura Naval Argentina (Argentine Naval Coastguard). Horizontal dashed lines show the winter (w) and summer (s) limits for the seasonally oscillations of the water table.

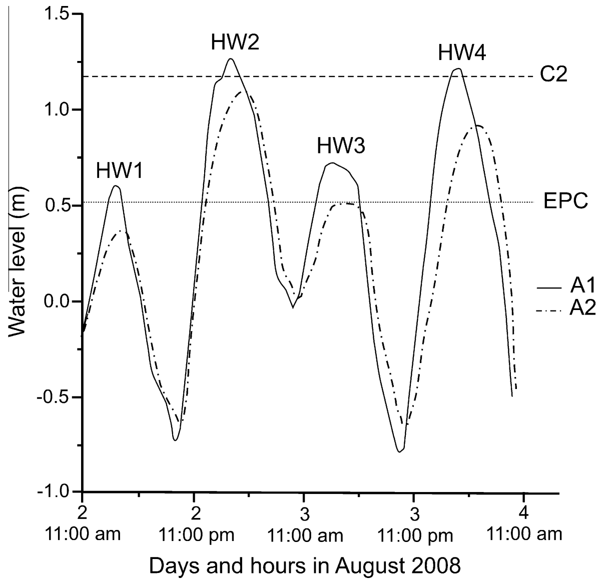

Fig. 3. Water levels at sites A1, A2, Canal 2 (C2) and El Palenque Canal (EPC) for 2–4 August 2008 (see Fig. 1 for location). HW = high water.

4. Results

4.1. Surface water

The tidal wave from the Rio de la Plata estuary enters the study area through the River Ajo and numerous tidal channels. During the measurement periods mentioned above, the observed tidal ranges in the middle course of the River Ajo (A1) (Fig. 1) varied between 0.50 and 2.10 m (Fig. 2). Measurements taken at the head (A2) (Fig. 1) and the middle course of the River Ajo (A1) show that tidal action extends up to 15 km from the river's outlet, with a lag time of approximately one hour between these two sites (Fig. 3 and Table 1). The gates located in the Canal 2 and the El Palenque Canal before their flowing into the River Ajo prevent the tide from entering the canals and keep the water level constant (Fig. 3). The water level in the Canal 2 is higher than those in the River Ajo and the El Palenque Canal. Because the Canal 2 is the only fresh water source for a nearby small town, the gates contribute to the storage of a suitable fresh water volume.

4.2. Groundwater

The regional groundwater flux is to the NNE towards the bay, with a hydraulic gradient of less than 10^{-4}. The relative positions of the surface and groundwater levels in the coastal plain show the prevalence of the phreatic discharge into the streams. Locally, the groundwater flux is from the sand sheets towards the coastal plain and from this to the tidal channels and the River Ajo (Fig. 4). The water table in the coastal plain is near the surface, at a depth between 0.3 and 0.8 m, whereas in the sand sheets it lies at a depth between 1.5 and 2.5 m, depending on the height of the sand sheet. The water table becomes deeper between October and March because of the decrease in precipitation and greater evapotranspiration during this warm semester (Figs. 2 and 4).

4.3. The relationship between surface water and groundwater

Next to the banks of the River Ajo, the tidal fluctuations affect the position of the water table, which can also oscillate seasonally between 0.3 m (in summer) and 0.7 m (in winter) over MSL (Fig. 2). The relationship between surface water and groundwater was analyzed on the basis of simultaneous measurements taken at the river and at monitoring wells located near the river banks. In the storm flat closer to point W1 (Fig. 1), the water table was measured along a transect of wells at 2 m, 5 m and 20 m from the erosion scarped river banks, whereas measurements in the low intertidal flats W3 and W5 (Fig. 1) were carried out at wells located at 2 m and 20 m from the river bank. Field observations in both types of river banks reveal that even at some high waters, if the water level of the river does not exceed that of the water table at the river bank the relationship between surface water and groundwater remains unchanged (high water 4 in Fig. 5 and Table 2; and high waters 2 and 4 in Fig. 6 and Table 3). Inversely, when the water level of the river at high water exceeds that of the water table, the tidal wave propagates into the aquifer and makes the water table rise. This modifies the position of the discharge point, resulting in a local reversal of the groundwater flux.

4.3.1. Storm flat

In the storm flat environment, where the river exhibits scarped banks, the tidal wave enters the aquifer and changes the level of the water table by a range that decreases with the distance from the river bank (high waters 1, 2 and 3 in Fig. 5, and Table 2).

However, in spite of the marked changes in the range of the water level of the river, 1.07 m, 0.82 m and 1.40 m at point A1

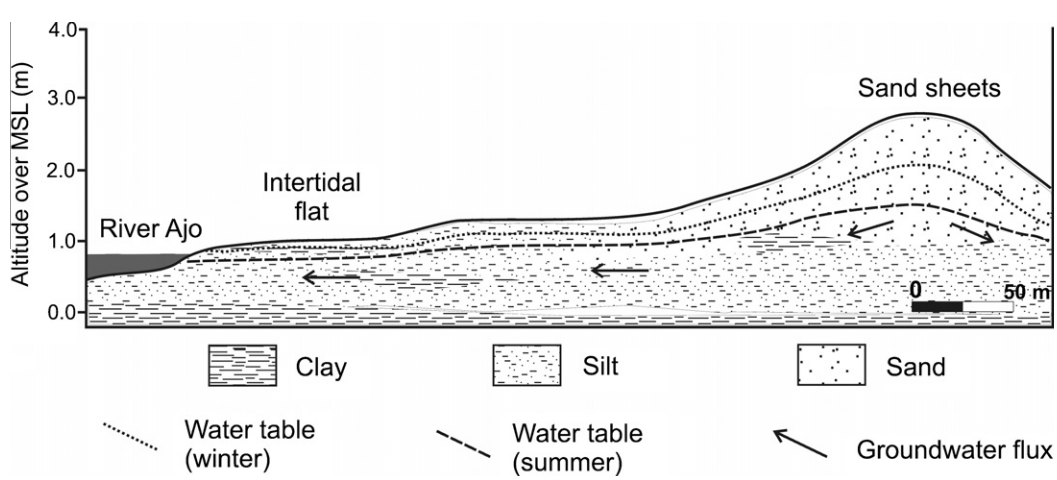

Fig. 4. Schematic illustration of groundwater flux in the vicinity of the River Ajo.

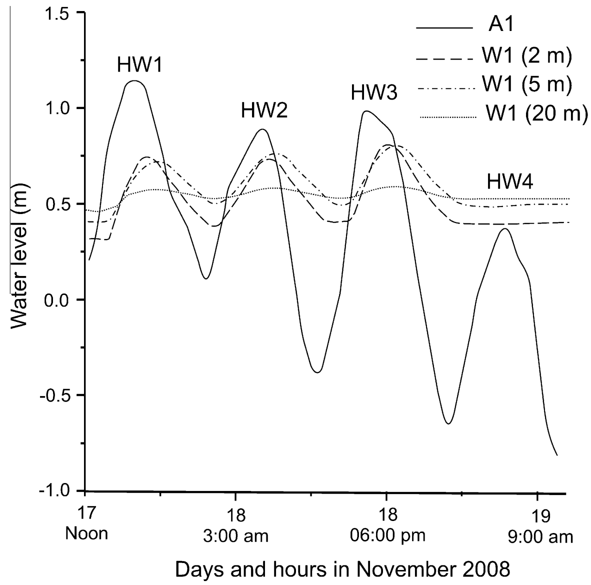

Fig. 5. Water levels at sites A1 and W1 for 17–19 November 2008 (see Fig. 1 for location). Numbers in parentheses for site W1 are distances from the river bank. HW = high water.

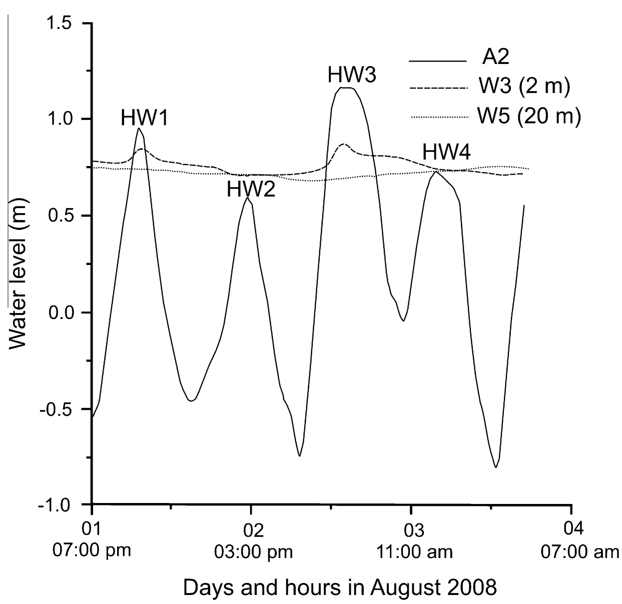

Fig. 6. Water levels at sites A2, W3 and W5 for 1–4 August 2008 (see Fig. 1 for location). Numbers in parentheses for sites W3 and W5 are distances from the river bank. HW = high water.

(Fig. 1), the consequent fluctuations of the water table are not so noticeable. At 2 m from the river bank the water table range oscillates between 0.35 and 0.40 m; at 5 m, between 0.25 and 0.31 m, and at 20 m, between 0.02 and 0.03 m. The average lag time of the tidal wave propagation in the aquifer is 1 h 20 min at 2 m, 2 h at 5 m, and 3 h 10 min at 20 m (Table 2). The rise of the water table with high water and its subsequent fall are nearly sinusoidal, with a period similar to that of the tide at the river (Fig. 5).

4.3.2. Intertidal flat

In the intertidal flat environment it was found that when the water level of the river exceeds the water table during high water with ranges of 1.07 m and 1.72 m at point A2 (Fig. 1), the subsequent fluctuations of the water table range from 0.10 m to 0.15 m at 2 m from the river bank, and from 0.03 to 0.05 m at 20 m from the river bank (high waters 1 and 3 in Fig. 6 and Table 3). At the well nearest to the river bank the time variation of the water table shows asymmetric peaks. The rise of the water table shows a lag time close to an hour, whereas the fall of the level lasts more than 14 h. Water level fluctuations at the well located 20 m from the river bank are not significant; the rise and fall of the water table have lag times varying between 8 and 10 h with respect to high tide at the River Ajo (Fig. 6 and Table 3).

5. Discussion

Management of water resources in a coastal wetland requires a precise knowledge of those factors that play a central role in the interrelation between surface water and groundwater. Mathematical models are useful tools for assessing and predicting natural processes in such environments. Very often, however, the lack of an adequate knowledge of the physical hydrology leads to an over-simplification of the variables affecting the complex hydrological processes that take place in a coastal wetland. Field studies help to verify said models, as well as to improve the knowledge of the properties of the modeled medium. The results obtained in this work show that the complex way in which the tidal wave flows into and out of the aquifer depends not only on the geomorphologic, geologic and hydrologic characteristics of the aquifer but also on the presence of structures built by organisms.

In the storm flat environments the tidal wave enters the erosion scarps and propagates into the phreatic aquifer as a sub-horizontal flow through the outcropped sediments (Fig. 7). Textbooks on hydrogeology (Custodio and Llamas, 1976; Todd and Mays, 2005) and analytical and numerical models (Jacob, 1950; Zhiyao et al., 2007; Hailong et al., 2008) consider that for this type of coasts the tide fluctuates symmetrically with respect to a mean level that coincides with the water table. Field data from the study area have shown that this condition is approximately satisfied during some tidal cycles. However, due to the large diurnal inequalities, tidal fluctuations are mostly asymmetric with mean oscillation levels above or below the water table.

Intertidal environments exhibit changing sedimentary facies in short distances that modify the horizontal hydraulic conductivity. Because of this, the tidal wave changes as it propagates into the aquifer. Mathematical models such as that developed by Trefry (1999) consider these horizontal heterogeneities by dividing the whole aquifer into an arbitrary finite number of homogeneous contiguous sub-aquifers, each of them with well-defined boundaries, a particular hydraulic conductivity and subject to appropriate

Table 1
Observed high waters at the middle course (A1) and head (A2) of the River Ajo during the period 2–4 August 2008 (see Figs. 1 and 3).

Site	High water 1			High water 2			High water 3			High water 4		
	Range (m)	Time (h min)	Lag time (h min)	Range (m)	Time (h min)	Lag time (h min)	Range (m)	Time (h min)	Lag time (h min)	Range (m)	Time (h min)	Lag time (h min)
A1	0.76	12:50 pm	–	1.30	01:15 am	–	1.00	02:30 pm	–	2.00	03:00 am	–
A2	0.50	01:45 pm	0:55	1.07	02:00 am	0:45	0.65	03:30 am	1:00	1.72	04:15 am	1:15

Table 2
Observed high waters at the middle course (A1) of the River Ajo and at three monitoring wells (W1) along a transect at 2, 5 and 20 m from the erosion scarped banks during the period 17–19 November 2008 (see Figs. 1 and 4).

Site	High water 1			High water 2			High water 3			High water 4		
	Range (m)	Time (h min)	Lag time (h min)	Range (m)	Time (h min)	Lag time (h min)	Range (m)	Time (h min)	Lag time (h min)	Range (m)	Time (h min)	Lag time (h min)
A1	1.07	04:30 pm	–	0.82	05:00 am	–	1.40	04:05 pm	–	0.88	04:50 am	–
W1 (2 m)	0.40	06:00 pm	1:30	0.35	06:15 am	1:15	0.37	05:30 pm	1:25	0	–	–
W1 (5 m)	0.31	06:45 pm	2:15	0.25	06:45 am	1:45	0.31	06:15 pm	2:15	0	–	–
W1 (20 m)	0.03	07:50 pm	3:20	0.02	08:00 am	3:00	0.03	07:10 pm	3:10	0	–	–

Table 3
Observed high waters measurements at the head of the River Ajo (A2) and in the low intertidal flats W3 and W5 during the period 1–4 August 2008 (see Figs. 1 and 6). Measurements were taken at 2 m (W3) and 20 m (W5) from the river bank.

Site	High water 1			High water 2			High water 3			High water 4		
	Range (m)	Time (h min)	Lag time (h min)	Range (m)	Time (h min)	Lag time (h min)	Range (m)	Time (h min)	Lag time (h min)	Range (m)	Time (h min)	Lag time (h min)
A2	1.07	02:00 am	–	0.65	03:30 am	–	1.72	04:15 am	–	0.50	03:35 pm	–
W3 (2 m)	0.10	03:05 am	1:05	0	–	–	0.15	05:10 am	0:55	0	–	–
W5 (20 m)	0.05	12:10 pm	10:10	0	–	–	0.03	02:10 pm	10:05	0	–	–

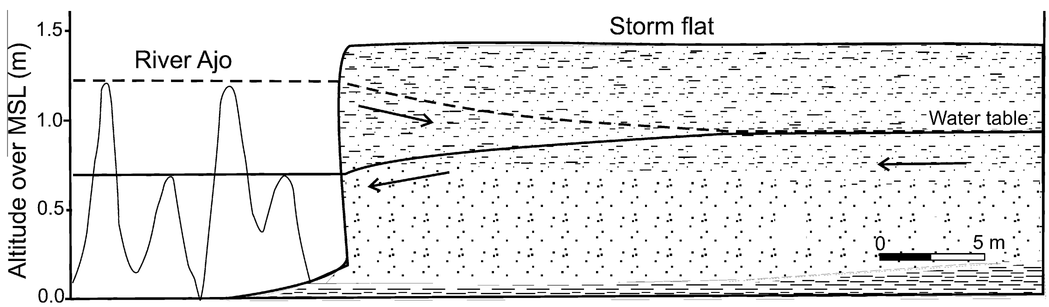

Fig. 7. Schematic illustration of groundwater flux at a scarped bank of the River Ajo. The sketch represents the influence of the mixed, predominantly semidiurnal tide (to the left) on the water table.

boundary conditions. The lithological descriptions from soundings in the study area reveal that compositional and granulometric changes in sediments are transitional, or that there is interfingering of facies. This lithological heterogeneity is typical of most of the intertidal environments.

The intertidal flat environments in the study area are characterized by the presence of numerous mud crab burrows. They form macrostructures that control the surface permeability of the substratum and the inflow of water into the phreatic aquifer. When the tide floods the swamp the water enters the aquifer as a straightforward vertical infiltration through the crab burrows, causing a quick rise of the water table. During low water, when the river level falls, the water table tends to recover its position by discharging the river as sub-horizontal groundwater flow (Fig. 8). The flow is slowed down by the low permeability of the clayey sediments. As the crab burrows are vertically oriented with respect to the ground surface, and are not interconnected, they do not constitute distinct pathways for preferential flow when the river level falls. Because of this, the groundwater flux into the river is very slow during ebb current and the recovery of the water table level takes a considerably greater than that required to fill the crab burrows and make the water table rise. Harvey and Nuttle (1995) and Xin et al. (2009) analyze the role of macropores of biological origin in the interrelation between surface water and

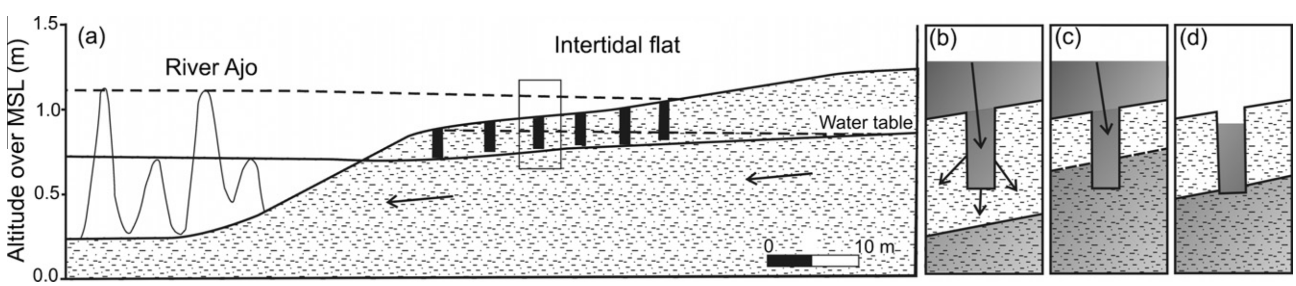

Fig. 8. Schematic illustration of groundwater flux at an intertidal flat of the River Ajo with crab burrows (black rectangles). The sketch represents the influence of the mixed, predominantly semidiurnal tide (to the left) on the water table. (a) At the highest high waters the river floods the intertidal flat. Water dynamics inside a typical crab burrow (within the small box) is explained further in the following items. (b) The water enters the crab burrows and penetrates the soil. (c) The water table level increases. (d) During falling tide, water draws down slowly because of the low permeability of the soil, and the water table recovers its level.

groundwater in intertidal environments. In these works the complexity given by the changes in the sedimentary facies is simplified.

Another matter that should be considered refers to the physical, chemical and biological processes that occur in the intertidal zone. The data provided by this work are of value to adjust the conceptual models of the hydrological functioning of coastal wetlands, and allow solute interchange processes, nutrient cycles and ecosystem habitats to be examined in detail, as has already been described for different intertidal zones (Mchenga and Tsuchiya, 2008; Wang et al., 2009; Otani et al., 2010).

Conceptually, the interrelation between surface water and groundwater in the intertidal flat of the River Ajo can be generalized to other crab-populated intertidal environments.

Changes in the water table level are representative of the time in which they were measured, and allow the general hydrologic functioning of the zone to be characterized. However, there is a drawback in the present work that should be mentioned. It refers to the influence of the time variation of crab burrows upon the hydrological response. The interrelation between surface water and groundwater, driven by the tidal cycle, and the subsequent soil infiltration through macropores is a dynamical process that varies according to the changes in the crab population.

In the future, the development of this matter should include not only the analysis of the hydrological response to space and time changes in the crab burrows, but also the experimental characterization of other nearby zones through an increase in soundings, pumping tests, determination of changes in the hydraulic conductivity and the installation of permanent surface and groundwater level gauges. The goal is to achieve a better quantitative assessment of the complex interrelation between surface water and groundwater in this kind of coastal wetlands.

6. Conclusions

The characteristics of the River Ajo swamp are representative of most of the Samborombon Bay estuarine wetland, and can be extended to other similar swamps. In this type of environments the tidal wave enters the coastal zone mainly through streams and tidal channels. Generally, these streams have either scarped banks or intertidal flat banks densely populated by crabs. The tide makes the stream level oscillate with the subsequent change in the direction of runoff. When the stream level oscillates above the water table of the phreatic aquifer the tide affects the groundwater flux near the river banks.

The way in which the tidal wave propagates into the aquifer, as well as the range of its influence is determined by the morphology of the banks and the hydraulic properties of the adjacent sediments. At the erosion scarps the tide propagates into the aquifer as a sub-horizontal flow through the pore space (effective porosity) of the sediments. Within the aquifer the tidal range depends mainly on the lithological characteristics of the sediments and the lateral variations of their hydraulic conductivity. At the intertidal flats, on the other hand, the tide enters the aquifer mainly as a sub-vertical flow through the crab burrows. Its range depends largely on the density, size and shape of the burrows. These characteristics can change throughout the year depending on the degree of biological activity.

The variability in the interrelationship between surface water and groundwater determines the hydrodynamic behavior of wetland ecosystems. As the chemical characteristics of groundwater and streams are different from those of either seawater or estuary water, the incoming tide causes the swamp to be a hydrochemically variable zone, which is clearly seen in the River Ajo marsh.

Human activities, as well as an apparently increasing occurrence of storm surges and floods due to climate change, will be challenging problems for the sustainable management of marsh environments in the near future. A good knowledge of the relationship between surface water and groundwater, and of the factors that could modify it, is of the utmost importance for the rational use of wetlands. Since marshes similar to the one in the River Ajo can be found in numerous coastline zones in the world, the results obtained in this work could also be applied on a regional scale.

Acknowledgments

The authors are very indebted to the Agencia Nacional de Promoción Científica y Tecnológica (National Agency for Scientific and Technological Promotion) and the Consejo Nacional de Investigaciones Científicas y Técnicas (National Council for Scientific and Technological Research) of Argentina for financially supporting this study by means of their grants, PICT 38256/05 and PIP 0414/08 respectively.

References

Ateie-Ashtiami, B., Volker, R.E., Lockington, D.A., 1999. Tidal effects on sea water intrusion in unconfined aquifers. J. Hydrol. 216, 17–31.
Bradley, C., 2002. Simulation of the annual water table dynamics of a floodplain wetland Narborough Bog, UK. J. Hydrol. 261, 150–172.
Carol, E., Kruse, E., Pousa, J., 2008. Environmental hydrogeology of the southern sector of the Samborombon Bay wetland, Argentina. Environ. Geol. 54, 95–102.
Carol, E., Kruse, E., Mas Pla, J., 2009a. Hydrochemical and isotopical evidence of ground water salinization processes on the coastal plain of Samborombón Bay, Argentina. J. Hydrol. 365, 335–345.
Carol, E., Kruse, E., Pousa, J., Roig, A., 2009b. Determination of heterogeneities in the hydraulic properties of a phreatic aquifer from tidal level fluctuations: a case in Argentina. Hydrogeol. J. 17, 1727–1732.
César, I., Armendáriz, L., Becerra, R., 2005. Bioecology of the fiddler crab Uca uruguayensis and the burrowing crab Chasmagnathus granulatus (Decapoda, Brachyura) in the Refugio de Vida Silvestre Bahía Samborombón, Argentina. Hydrobiologia 545, 237–248.
Custodio, E., Llamas, M., 1976. Hidrología Subterránea. Omega, Madrid.
Dolphin, T.J., Hume, T.M., Parnell, K.E., 1995. Oceanographic processes and sediment mixing on a sand flat in an enclosed sea, Manukau Harbour, New Zealand. Mar. Geol. 128, 169–181.
Gardner, L.R., 2005. Role of geomorphic and hydraulic parameters in governing pore water seepage from salt marsh sediments. Water Resour. Res. 41, W07010. doi:10.1029/2004WR003671.
Gardner, L.R., 2007. Role of stratigraphy in governing pore water seepage from salt marsh sediments. Water Resour. Res. 43. doi:10.1029/2006WR005338, W07502.
Gardner, L.R., Porter, D.E., 2001. Stratigraphy and geologic history of a southeastern salt marsh basin, North Inlet, South Carolina, USA. Wetlands Ecol. Manage. 9, 371–385.
Genereux, D., Slater, E., 1999. Water exchange between canals and surrounding aquifer and wetlands in the Southern Everglades, USA. J. Hydrol. 219, 153–168.
Guerrero, R., Acha, E., Framiñan, M., Lasta, C., 1997. Physical oceanography of the Rio de la Plata estuary, Argentina. Cont. Shelf Res. 17, 727–742.
Hailong, L., Boufadel, M., Weaver, J., 2008. Tide-induced seawater–groundwater circulation in shallow beach aquifers. J. Hydrol. 352, 211–224.
Harvey, J., Nuttle, W., 1995. Fluxes of water and solute in a coastal wetland sediment. 2. Effect of macropores on solute exchange with surface water. J. Hydrol. 164, 109–125.
Holden, J., 2005. Controls of soil pipe frequency in upland blanket peat. J. Geophys. Res. 110, F01002. doi:10.1029/2004JF000143.
Hughes, C.E., Binning, P., Willgoose, G.R., 1998. Characterisation of the hydrology of an estuarine wetland. J. Hydrol. 211, 34–49.
Iggy Litaor, M., Eshel, G., Sade, R., Rimmer, A., Shenker, M., 2008. Hydrogeological characterization of an altered wetland. J. Hydrol. 349, 333–349.
Jacob, C.E., 1950. Flow of ground water. In: Rouse, H. (Ed.), Engineering Hydraulics. Wiley, New York.
Langevin, C., Swain, E., Wolfert, E., 2005. Simulation of integrated surface-water/ground-water flow and salinity for a coastal wetland and adjacent estuary. J. Hydrol. 314, 212–234.
Mchenga, I., Tsuchiya, M., 2008. Nutrient dynamics in mangrove crab burrow sediments subjected to anthropogenic input. J. Sea Res. 59, 103–113.
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. J. Hydrol. 316, 108–128.
Mulligan, A., Evans, R., Lizarralde, D., 2007. The role of paleochannels in groundwater/seawater exchange. J. Hydrol. 335, 313–329.
Nielsen, P., 1990. Tidal dynamics of the water table in beaches. Water Resour. Res. 26, 2127–2134.

Odum, W.E., Odum, E.P., Odum, H.T., 1995. Nature's pulsing paradigm. Estuaries 18, 547–555.
Otani, S., Kozuki, Y., Yamanaka, R., Sasaoka, H., Ishiyama, T., Okitsu, Y., Sakai, H., Fujiki, Y., 2010. The role of crabs (*Macrophthalmus japonicus*) burrows on organic carbon cycle in estuarine tidal flat. Estuar Coast. Shelf. Sci. 86, 434–440.
Parker, G., 1979. Geología de la planicie costera entre Pinamar y Mar de Ajó, Provincia de Buenos Aires. Rev. Assoc. Geol. Argent. (RAGA) 34, 167–183.
Perillo, G.E., Minkoff, D.R., Piccolo, M.C., 2005. Novel mechanism of stream formation in coastal wetlands by crab–fish–groundwater interaction. Geo-Mar. Lett. 25, 214–220.
Qualls, R.G., Richardson, C.J., 2000. Phosphorus enrichment affects litter decomposition, immobilization, and soil microbial phosphorus in wetland mesocosms. Soil Sci. Soc. Am. J. 64, 799–808.
Richardson, C.J., Reiss, P., Hussain, N.A., Alwash, A.J., Pool, D.J., 2005. The restoration potential of the Mesopotamian marshes of Iraq. Science 307, 1307–1311.
Sutula, M., Day, J.W., Cable, J., Rudnick, D., 2001. Hydrological and nutrient budgets of freshwater and estuarine wetlands of Taylor Slough in Southern Everglades, Florida (USA). Biogeochemistry 56, 287–310.
Todd, D.K., Mays, L.W., 2005. Groundwater Hydrology. Wiley, New York.
Trefry, M.G., 1999. Periodic forcing in composite aquifers. Adv. Water Resour. 22, 645–656.
Vandenbohede, A., Lebbe, L., 2007. Effects of tides on a sloping shore: groundwater dynamics and propagation of the tidal wave. Hydrogeol. J. 15, 645–658.
Violante, R., Parker, G., Cavallotto, J., 2001. Evolución de las llanuras costeras del este bonaerense entre la bahía de Samborombón y la laguna de Mar Chiquita durante el Holoceno. Rev. Assoc. Geol. Argent. (RAGA) 56, 51–66.
Wang, J., Tang, L., Zhang, X., Wang, C., Gao, Y., Jiang, L., Chen, J., Li, B., 2009. Fine-scale environmental heterogeneities of tidal creeks affect distribution of crab burrows in a Chinese salt marsh. Ecol. Eng. 35, 1685–1692.
Woodroffe, C., Davies, G., 2009. Coastal Wetlands: An Integrated Ecosystem Approach. Elsevier, Oxford, UK.
Xin, P., Jin, G., Li, L., Barry, D.A., 2009. Effects of crab burrows on pore water flows in salt marshes. Adv. Water Resour. 32, 439–449.
Zhiyao, S., Ling, L., Jun, K., Honggui, Z., 2007. A new analytical solution of tidal water table fluctuations in a coastal unconfined aquifer. J. Hydrol. 340, 256–260.