Wetlands (2021) 41: 83
https://doi.org/10.1007/s13157-021-01482-x

WETLAND HYDROLOGY AND GEOMORPHOLOGY

Water Dynamics in a Coastal Wetland in the "Parque Costero del Sur" Biosphere Reserve, Argentina

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Received: 16 December 2020 / Accepted: 29 July 2021 / Published online: 11 August 2021

Abstract

Interactions and exchanges between surface water, groundwater, and the atmosphere are some of the most relevant functions that regulate environmental characteristics in wetlands. These functions depend on environmental attributes such as topography, geological-geomorphological setting and, in the case of coastal wetlands, the relationship with tidal flows. The aim of this work is to analyse the water flows in different landscape units of the wetland in the coastal plain of the Río de la Plata estuary within the Parque Costero del Sur biosphere reserve. For this purpose, monthly water balances and groundwater level measurements were compared with daily precipitation and tidal height data from the Río de la Plata estuary. The results show how water dynamics in the wetland responds to different geological-geomorphological and climatic controls. The main inlets and outlets of water, as well as the flow exchanges, vary according to the different landscape units, forming a complex system on which the main ecological features depend.

Keywords Coastal plain · Río de la Plata estuary · Landscape units · Groundwater flow

Introduction

Wetlands are among the most important ecosystems on earth, both for the goods they produce, e.g., fish, fuelwood, timber, tourist attractions and, the services they provide, e.g., flood alleviation, groundwater recharge, retention of pollutants (Barbier et al. 2011). They play an important role as purifiers in hydrological and biogeochemical cycles and constitute important biodiversity reserves (Mitsch and Gosselink 2015).

Wetlands comprise areas where water covers the soil or is present either at or near the surface of the soil all year or for varying periods during the year in which water saturation largely determines how the soil develops and the types of plant and animal communities (Brinson 1993; Ramsar Convention Secretariat 2006). The characteristics of the wetland system can be clustered into three main groups: components, functions, and attributes. Components include soil, water, plants, and animals. The interactions between them can be expressed as functions that include nutrient cycles and exchanges between surface water, groundwater, and the atmosphere, while attributes correspond to factors such as biodiversity, topography, and other physiographic features (Barbier et al. 1997).

The interaction between surface water, groundwater, and the atmosphere constitutes one of the most important functions that play a key role in regulating the main environmental aspects in wetlands (Hunt et al. 1999; Brinson and Malvárez 2002; Amatya et al. 2020). Surface water bodies are connected with groundwater and as a result, they form an integral fraction of the groundwater flow systems (Winter et al. 1998). As an example, if groundwater is polluted, surface water may consequently be affected (Meinikmann et al. 2015).

Both surface water and groundwater flow are largely controlled by topography and permeability, showing wide spatial and temporal variability in their dynamics depending on the terrain they interact with (Custodio and Llamas 1976; Tóth 1999). Topography and permeability are determined, in turn, by geological and soil properties, associated with wetlands

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geomorphological setting (Brinson 1993; Wolanski et al. 2009). Water balance into and out of the system is also controlled by climatic conditions, which is why it is essential to understand its effects on groundwater flow systems to comprehend surface water - groundwater interactions (Winter 1999; Rodríguez-Rodríguez et al. 2021). Particularly, in coastal wetlands, factors related to tidal influence are added, and therefore, the interactions between system components become even more complex (Rotzoll and El-Kadi 2008; Wolanski et al. 2009).

The coastal plain of the Río de la Plata, located in the northeast coast of Buenos Aires, Argentina, is an area of protected wetlands, which are part of the "Parque Costero del Sur" biosphere reserve within the UNESCOS's Man and the Biosphere (MAB) Programme (www.unesco.org/mab/). Its relevance lies in the fact that a significant number of environments are placed in a reduced area with great biodiversity (Haene 2006; Athor 2009). The presence of different environments is due to the evolution of the Argentinian coastline of the Río de la Plata estuary, as a result of the transgressive and regressive events which occurred during the Holocene (Cavallotto et al. 2004; Violante and Parker 2004). These events configured a continuous coastal plain along the right margin of the Río de la Plata estuary.

The Holocene geomorphological units consist of an ancient tidal flat, a beach ridge plain, and a marsh (Fig. 1), each of them showing specific lithological (Cellone et al. 2018) and hydrochemical characteristics (Cellone et al. 2019). These units lie on a transgressive surface, carved on a Pleistocene loessic plain, which is exposed in the wetland boundary sectors. The ancient tidal flat corresponds to an area of low topography, currently disconnected from the estuary. It is composed of clayey sediments on the surface that become silty at a depth of 1 m. The beach ridge plain consists of elongated ridges parallel to the coast, elevated about 6 m above sea level (hereinafter m asl), and are characterized by shell and sand deposits. The marsh is a narrow fringe parallel to the coast composed of clayey sediments and it is periodically flooded during high tides. The estuary has a semi-diurnal micro-tidal regime with diurnal inequalities, with mean amplitudes of 0.7 m (Servicio de Hidrografía Naval 2001). In this way, the variability in the geological and geomorphological features that occur in the coastal plain determines the existence of different landscape units within the wetland.

The aim of this work is to analyse the water flow dynamics in the different landscape units of the wetland placed in the coastal plain of the Río de la Plata estuary in the Parque Costero del Sur biosphere reserve. Properly understanding the behaviour of the water dynamics in this wetland will help to ensure sustainable management of its valuable resources.

Methodology

Based on the geomorphological and geological characteristics of the study area, 28 piezometers were placed at depths between 2 and 5 m, covering the different landscape units present in the wetland. The piezometers were levelled to the mean sea level at the end of the fieldwork using a differential global positioning system (GPS Emlid REACH RS+). To analyse flow exchanges between the different landscape units, the piezometers were arranged in three main transects approximately perpendicular to the coast (Fig. 1). Boreholes were made by manual drilling and slotted PVC pipes with gravel prefilter were used for the installation of the piezometers. Sediment samples were taken when lithological changes were observed in order to study the different soil textures.

To define periods of water deficit and surpluses and verify moments in which rainwater infiltration and consequently the recharge of the phreatic aquifer mainly occurs, a water balance was performed between 2007 and 2016. The Thornthwaite and Mather (1957) formula was used to calculate the potential evapotranspiration. The proposed methodology is adequate given the lack of meteorological data in the area, which only includes daily temperature and precipitation records. The meteorological data corresponds to the station located in the Base Aeronaval Punta Indio at 8 km from the study area, which is part of the Servicio Meteológico Nacional (National Meteorological Service) station network.

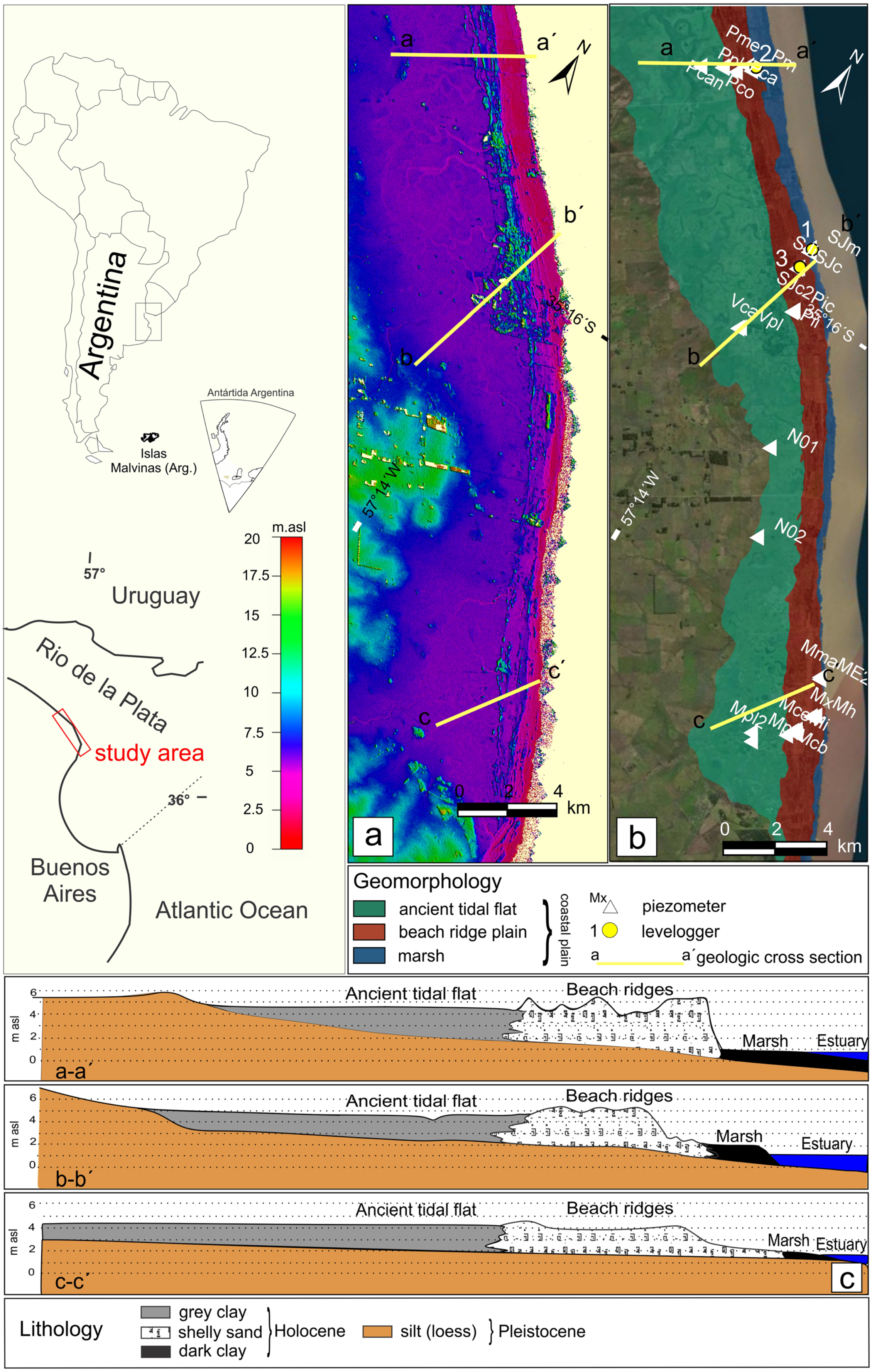
The potential evapotranspiration was calculated by the following formula: PET = K.ε.

where:

$$\begin{aligned}
&\varepsilon = 16(10\mathrm{t}/\mathrm{I})^{\mathrm{a}}\\
&\mathrm{I} = \Sigma\,\mathrm{i}\\
&\mathrm{i} = (\mathrm{t}/5)^{1.514}\\
&\mathrm{a} = \left(6.75\ 10^{-9}\right)\mathrm{I}^3-\left(7.71\ 10^{-5}\right)\mathrm{I}^2+\left(1.792\ 10^{-5}\right)\mathrm{I}+0.49239\\
&\mathrm{K} = (\mathrm{N}/12)(\mathrm{d}/30)\mathrm{d}
\end{aligned}$$

and where t is the average monthly temperature in degrees Celsius, N is the maximum number of hours of sunshine according to latitude and month, d is the number of days in the month and I is a thermal index that depends on the average monthly temperatures of the year being considered.

In order to evaluate soil water reserves, different textural parameters were considered to determine permanent wilting point and field capacity and, therefore, the available water capacity of the soil. Textural characteristics of the surface horizons sediments were considered from the obtained soil samples. Based on Saxton and Rawls (2006), for this texture, the field capacity was 12% and the permanent wilting point was 5% and the available water (field capacity less the permanent wilting point) was 7%. If a root zone of 50 cm and an apparent density of 1.46 g/cm^3 is considered for this texture, the available soil water or reserve would be around 51 mm. Given the low topography of the area and the absence of an


Argentina
Antártida Argentina
Islas Malvinas (Arg.)
57°
Uruguay
Rio de la Plata
study area
36°
Buenos Aires
Atlantic Ocean
m.asl
20
17.5
15
12.5
10
7.5
5
2.5
0
a
a´
b
b´
c
c´
N
35°16´S
57°14´W
0 2 4 km
a
Pme2Pm
Pcan Pco
Pca
1
3
SJm
SJc
SJc2Pic
Pi
Vca Vpl
N01
N02
MmaME2
MxMh
Mce Mi
Mpl2 Mp
Mcb
b
Geomorphology
ancient tidal flat
beach ridge plain
marsh
coastal plain
Mx piezometer
1 levelogger
a a´ geologic cross section
Ancient tidal flat
Beach ridges
Marsh
Estuary
m asl
6
4
2
0
a-a´
b-b´
c-c´
c
Lithology
grey clay
shelly sand
dark clay
Holocene
silt (loess)
Pleistocene

◀ **Fig. 1** Location of the study area: **a** TanDEM-X digital elevation model (Krieger et al. 2007) and location of geological cross-sections, **b** Main landscape units of the coastal plain in the Río de la Plata estuary and location of the piezometers and water table data loggers, **c** Geological cross-sections of the coastal plain

integrated drainage network, surface runoff was not believed to be significant, thus the water surplus was interpreted as infiltration or as rejected recharge.

The balance was carried out as follows:

$$\begin{aligned}&\mathrm{ET} = \mathrm{PET} \text{ if } \mathrm{P} > \mathrm{PET}\\ &\mathrm{ET} = \mathrm{P} + [\Delta\mathrm{R}] \text{ if } \mathrm{P} < \mathrm{PET}\\ &\mathrm{P}-\mathrm{ET} = \Delta\mathrm{R}\\ &\mathrm{P}-\mathrm{ET} = \mathrm{Ws} \text{ if R reaches 51 mm}\end{aligned}$$

Where:

P	precipitation
PET	potential evapotranspiration
ET	evapotranspiration (real)
R	water reserve or available water
ΔR	variation in the water reserve from one month to the next
Ws	water surplus

To evaluate the hydroperiod of the wetland, satellite images from Landsat 8 were analysed along with water balances in which different waterlogging conditions were identified for the year 2016, a year with mean annual precipitation values. In addition, for the same year, Normalized Difference Moisture Index (NDMI) was performed to evaluate moisture levels in vegetation. The index uses NIR and SWIR bands to create a ratio designed to mitigate illumination and atmospheric effects (Wilson and Sader 2002; Skakun et al. 2003). It was calculated specifically for the ancient tidal flat unit.

$$\begin{aligned}&\mathrm{NDMI} = (\mathrm{NIR}-\mathrm{SWIR1})/(\mathrm{NIR} + \mathrm{SWIR1})\\ &\mathrm{NIR} = \text{pixel values from the near infrared band}\\ &\mathrm{SWIR1} = \text{pixel values from the short-wave infrared 1 band}\end{aligned}$$

Groundwater level measurements were carried out during the summer and winter months employing a water level meter, and on the other hand, three water level data loggers (Solinst Leveloggers, model 3001) were installed in three piezometers. Two of the data loggers were located in the marsh, one close to the estuary and the other in a more distal sector (indicated as 1 and 2 in Fig. 1b), while the third was placed in the beach ridge plain (indicated as 3 in Fig. 1b). At the same time, a barometric pressure logger was installed to correct the collected data from leveloggers (Solinst Barologger, model 3001). The level data were automatically corrected using the barometric pressure records to obtain the real level values using Solinst Levelogger 3.4.1 software. Based on the periodic level measurements, three groundwater flow profiles were constructed in transects a-a´, b-b´, and c-c´ (Fig. 1) and isophreatic maps for deficit and water surplus periods.

In order to characterize the dynamics of the estuary and determine its influence on groundwater in the wetland, hourly tidal data of the estuary were studied for the years 2015 and 2016. The tidal data was collected by the Servicio de Hidrografía Naval (Naval Hydrography Service), and corresponds to the tide station of Atalaya, with coordinates 35° 00′ 55” S and 57° 32′ 10” W. Conversely, to characterize the relationship between groundwater and rainwater, daily precipitation data collected by the National Meteorological Service were used for the years 2015 and 2016 as well. Subsequently, the available information was integrated in order to construct graphs of the water table - tide level and water table - precipitation relationships and determine the main processes that regulate water dynamics in the wetland.

Results

For the 2007–2016 period, water balances indicated an average rainfall of 1049 mm y^{-1} while PET was 821 mm y^{-1} and ET was 779 mm y^{-1}. The water surpluses were in the order of 270 mm y^{-1} concentrated between June and November (winter and spring). Conversely, the total water deficit was 42 mm in December and January (summer) (Fig. 2a). The analysis of Landsat images showed that surplus periods coincided with waterlogging conditions in the wetland, particularly in the ancient tidal flat. In this area, during autumn and winter tidal channels were covered by water, while during spring and summer, as evapotranspiration increased, water excess was evacuated (Fig. 2c). The results of the NDMI were also consistent with the water balance. Moisture levels in vegetation remained high except during summer, which indicates that most of the year the soil was moist and there was no water deficit (Fig. 2b).

Water table measurements between summer and winter showed variations mainly in the beach ridge plain, while in the ancient tidal flat they were less significant, and in the marsh daily variations coincide with tidal oscillations. Overall, the water table varied between 0.35 and 3.50 m asl during summer. The highest values occurred in the ancient tidal flat, the intermediate values in the beach ridge plain, and the lower values in the marsh area. In this way, groundwater flow showed a discharge towards the estuary, although with an extremely low gradient (0.001) (Fig. 3a). A rise in the water table was observed during winter since the water table oscillated between 1.1 and 4.1 m asl. In this period, the highest levels were found in the beach ridge plain area, where a groundwater flow divide was marked showing a discharge both towards the marsh and the ancient tidal flat (Figs. 3 and 4). During summer the water table was between 2 and 4 m deep in the ancient tidal flat and between 2 and 5 m deep in the

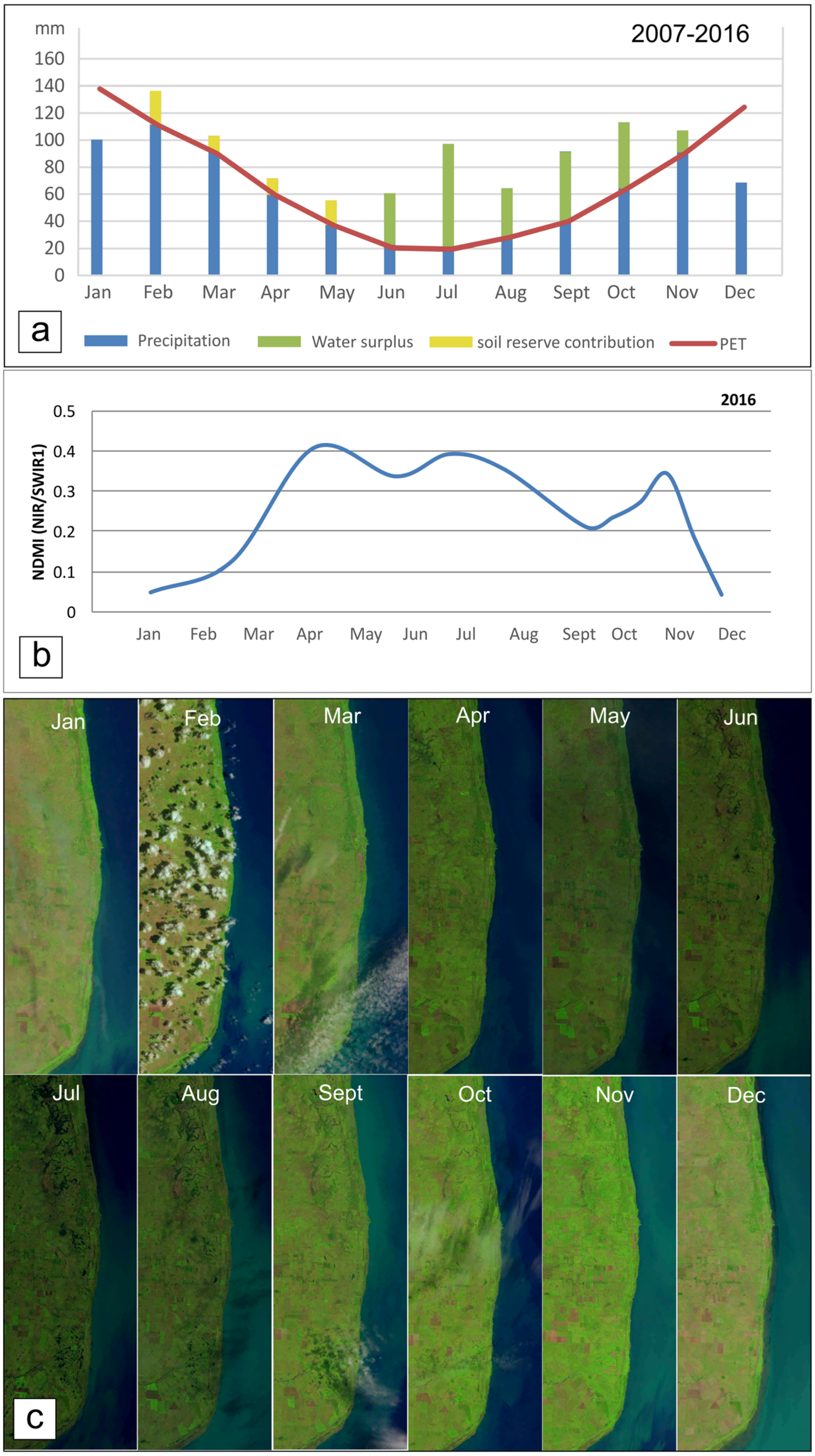


Fig. 2 **a** Average monthly water balances for the period 2007–2016 (10 years). PET: potential evapotranspiration. **b** Normalized Difference Moisture Index (NDMI) for a sector of the wetland for the year 2016. **c** Landsat images series for the year 2016

beach ridge plain while during winter it was between 0 and 1 m deep in the ancient tidal flat and between 0.5 and 2 m deep in the main ridges. The shallow levels in each landscape unit corresponded to the tidal channels in the ancient tidal flat and the spaces between ridges in the beach ridge plain. In the marsh, the water table remained near the surface (< 1 m deep) the whole year.

From the analysis of the water level data loggers, and tide and rainfall records it was observed that water table levels varied according to the landscape unit analysed. In the marsh

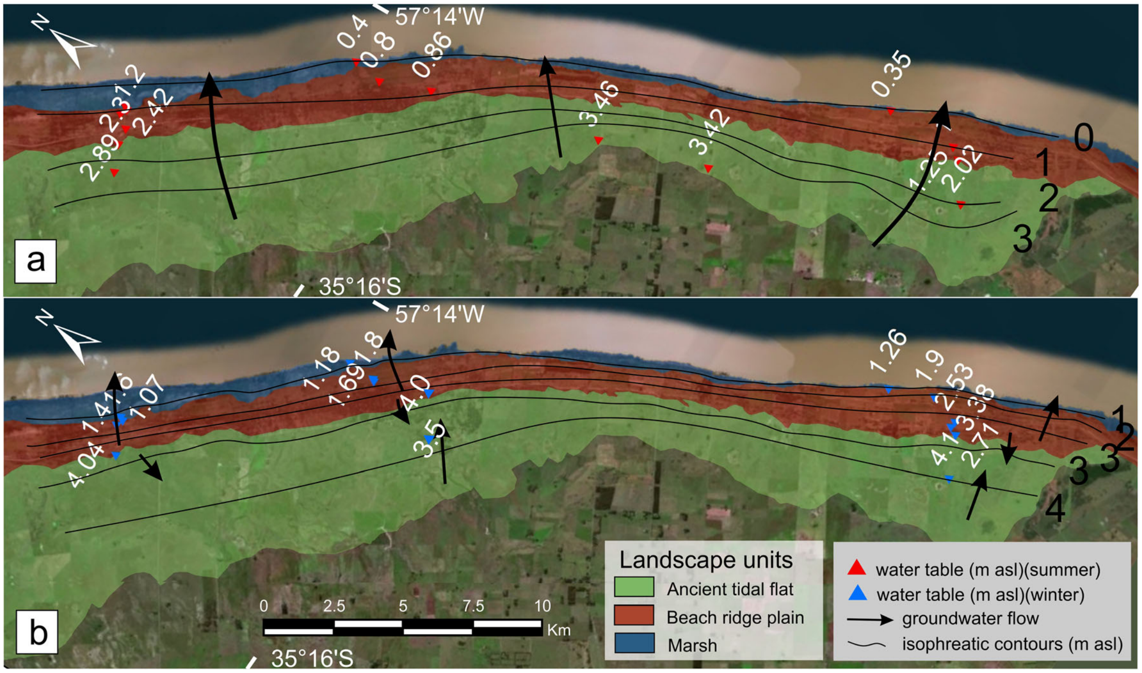


Fig. 3 Isophreatic map and groundwater flow directions for the summer (**a**) and winter (**b**) periods

sector located next to the estuary (levelogger 1, Fig. 1), asymmetric peaks of up to 50 cm were registered, which generally overlapped with high tides of 2 m asl or higher. Then, there was a continuous decrease in the water table levels followed by smaller amplitude oscillations (Fig. 5). Rises in the water table due to rainfall were practically negligible to null (Fig. 5).

In the marsh distal sector (levelogger 2, Fig. 1) it was observed that groundwater dynamics differed from that of the sector closer to the estuary. In this area, the water table showed very attenuated level oscillations with values between 1 and 3 cm attributable to the tidal regime (Fig. 6a and b), and a maximum oscillation of 20 cm that coincided with an extraordinary high tide of 2.5 m asl (Fig. 6a). On the other hand, no oscillations in the water table coincided with rainfall records (Fig. 6c).

In the beach ridge plain (levelogger 3, Fig. 1) there was no coincidence between water table oscillations and tidal oscillations (Fig. 7a and b). On the contrary, in this unit water table level increases occurred simultaneously with the highest rainfall records (Fig. 7c), although there was a general decrease in the water table height from September to December (spring to summer).

Discussion

Surface water – groundwater dynamics and exchanges between vertical and lateral flows are the result of complex systems of interactions between wetland components that, subsequently, are responsible for maintaining their ecological integrity (Brinson 1993; Euliss et al. 2004; Cook and Hauer 2007; Jolly et al. 2008; Acworth 2009; Hayashi et al. 2016). Within the coastal plain wetlands in the Parque Costero del Sur biosphere reserve, water dynamics and hydroperiods are determined by numerous factors. Among these, geomorphology, tidal action, water regime, and soil permeability determine the infiltration processes or the accumulation of water on the surface, being also factors that act in an integrated manner, constituting a complex system on which depend the main ecological features.

While the regional groundwater flow occurs towards the Río de la Plata estuary, as indicated by the decrease in water table near this sector, during periods of water surpluses (winter), the beach ridge plain acts as a preferential recharge zone of the aquifer causing a rise in the water table leading to the conformation of a groundwater flow divide. In this way, during these periods, groundwater flow is both towards the marsh area as towards the ancient tidal flat and the regional groundwater flow is also slower, due to the lower gradients. Subsequently, when the deficit period begins, the water table tends to decrease in the ridges. In addition to groundwater discharge, the ancient tidal flat receives surface inputs from surrounding basins located in the most continental sector. In this sector of the ancient tidal flat, surface runoff is hindered by the beach ridge plain. This, added to the low permeability of the surface sediments of this unit, causes frequent flooding promoted also by the accumulation of surface drainage and precipitation as it is shown in the analysis of Landsat images where it is observed that most tidal channels are covered by a sheet of water. During surplus periods, the soil remains moist

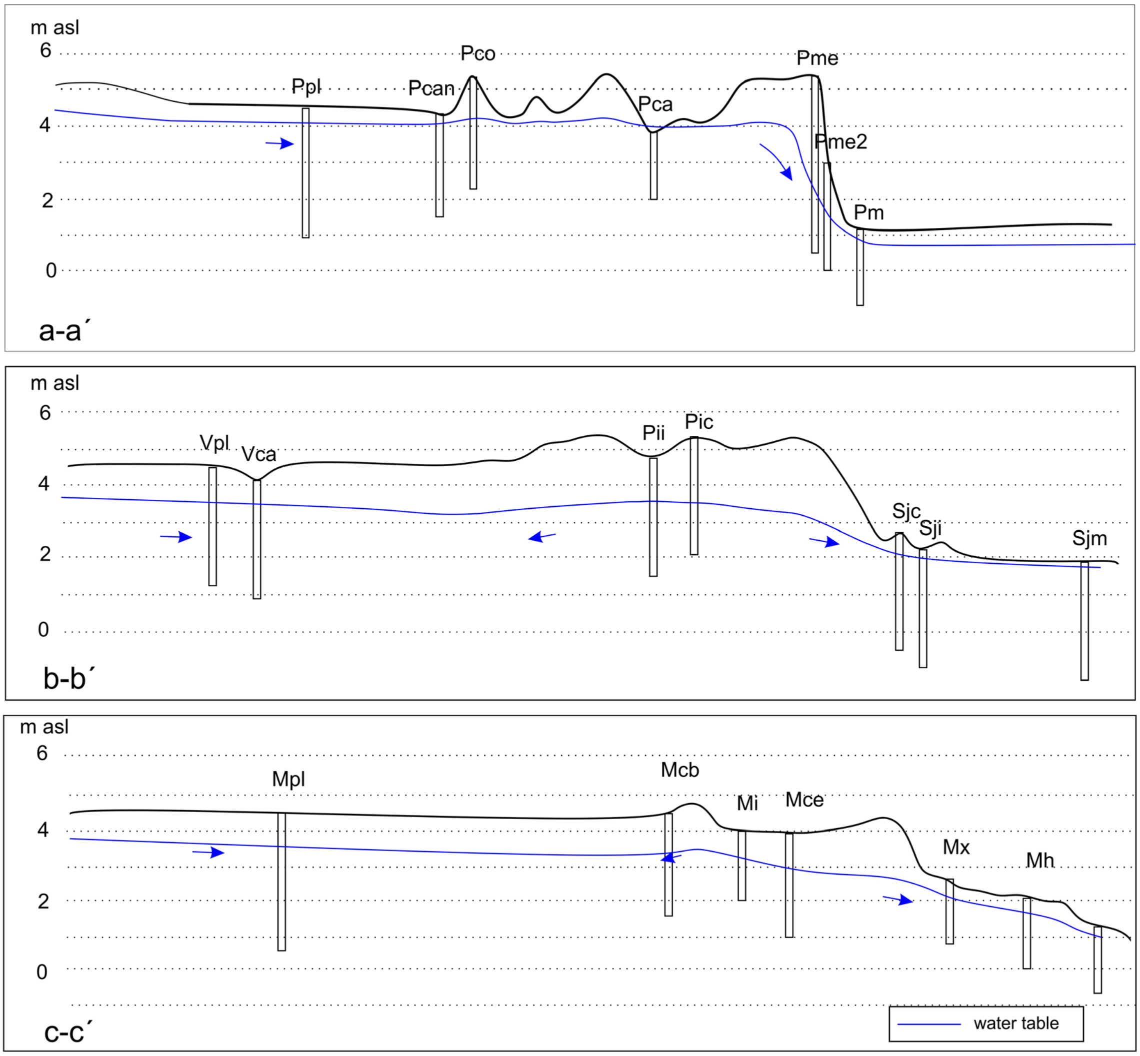


Fig. 4 Groundwater flow profiles for transects detailed in Fig. 1a for the winter period. Piezometers' location is also detailed in Fig. 1a

and the water table is shallow as indicated by the soil water balance, the NDMI, and water table measurements. In the beach ridge plain, the sandy-shelly sediments favour rainwater infiltration because of the higher permeability of these coarse materials. Infiltration process can be observed in groundwater level records, where the water table rises when precipitation exceeds 40 mm. No water table rises are registered when rainfall is of lesser magnitude, thus probably it is retained by

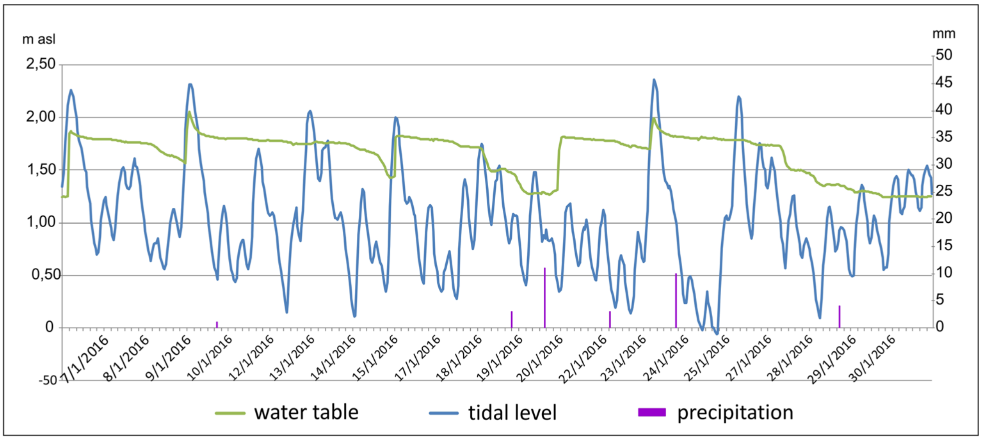


Fig. 5 Water table data logger recorded in a sector of the marsh near the estuary (levelogger 1). Water table - tidal level - precipitation relationship

Fig. 6 Water table data logger records in a sector of the marsh further away from the estuary (levelogger 2). **a** Relationship between water table data logger records and tidal level. **b** Detail of the water table - tidal level relationship of the dotted box in Fig. 6 a. **c**) Water table - precipitation relationship

the soil, contributing to soil water reserves without reaching the aquifer. This process of rapid infiltration of rainwater is similar or equivalent to that observed in other wetlands in coastal zones linked to beach ridge or dune systems, where their coarse materials allow rapid infiltration of rainwater and the consequent formation of freshwater lenses above saline or brackish groundwater (Wallis et al. 1991; Röper et al. 2012; Greggio et al. 2018).

Additionally, the decrease in the water table from spring to summer is consistent with the change from a water surplus period to a water deficit period, as indicated by the water balances for the period analysed. In this way, rainwater infiltration occurs mostly during winter and spring, causing a water table rising; while, during summer, when evapotranspiration is higher, a decrease in the water table is observed. In particular, the year 2015 in which levelogger 3 records were carried out, turned out to be relatively dry. This situation also favoured the rapid decrease in the water table since recharge from rainwater is lower. On the other hand, the marsh sector located next to the estuary is flooded during extraordinary high tides, and subsequently, the estuary water infiltration occurs. Thereby, the column of water over the marsh sediments produces a quick rise in the water table followed by a slow decrease during low tide and lower high tides due to groundwater discharge towards the estuary. This phenomenon has been registered in other marsh sectors in the estuary (Carol

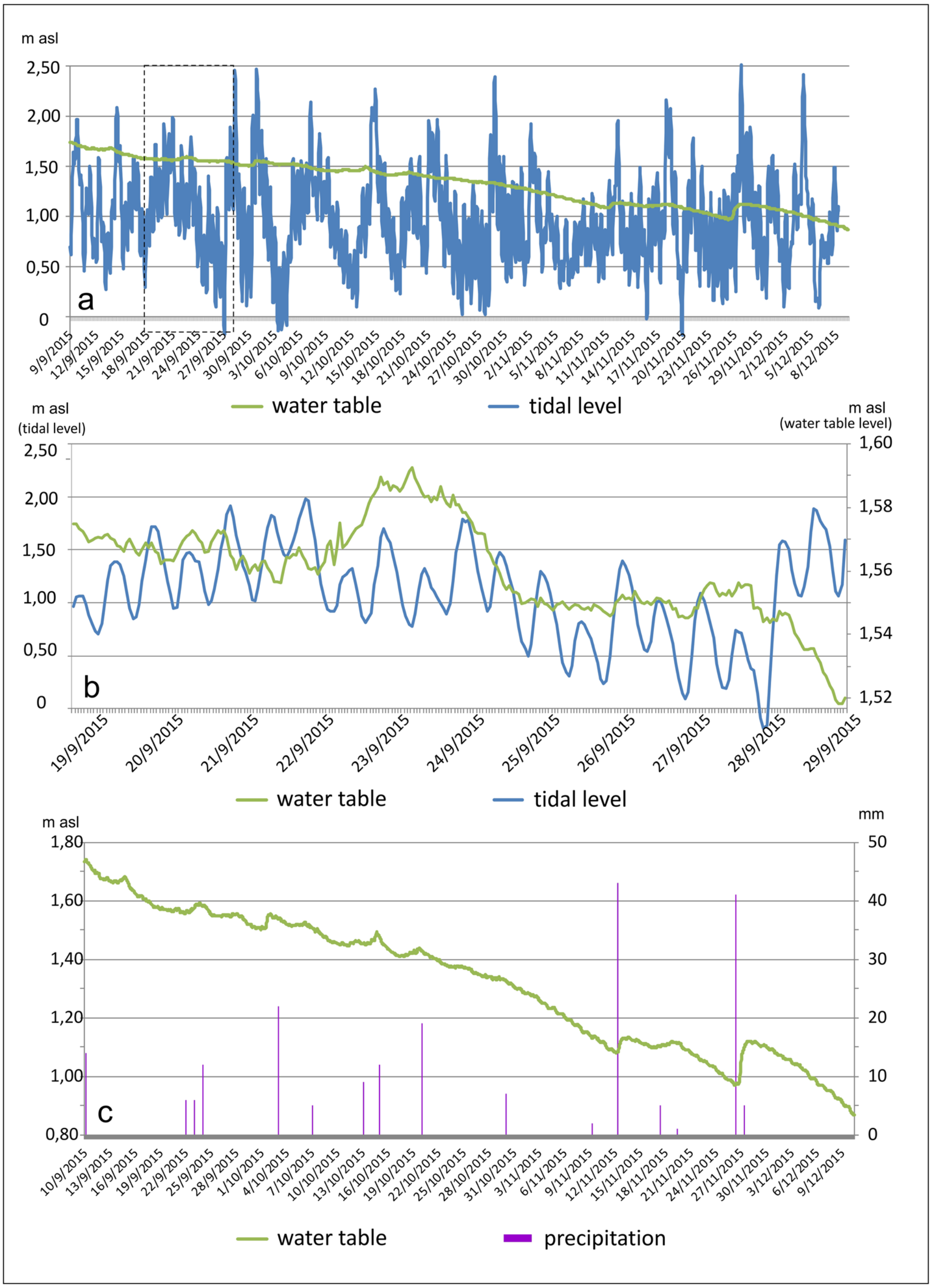


Fig. 7 Water table data logger records in the beach ridge plain (levelogger 3). **a** Relationship between water table data logger records and tidal level. **b** Detail of the water table -tidal level relationship. **c** Water table - precipitation relationship

et al. 2012) and is a well-known common behaviour of marsh environments (Wilson and Gardner 2006; Van Putte et al. 2020). The hydroperiod of this sector of the wetland is determined by the occurrence of high tides and when these are higher than the terrain level, which in the marsh it is about 2 m asl. These events coincide with spring tides and storm surges and have an occurrence of approximately 40 events a year in the period analysed. In addition, during high tides of lower amplitude, minor oscillations in the water table are recorded, which could be explained by a hydraulic and mechanical effect induced by the tide as a result of the force performed by the high tide water column on the sediments that contain the aquifer and that extend towards the platform sector of the estuary (Guarracino et al. 2012). These oscillations, unlike those produced by flooding of the marsh, do not involve water exchanges with the estuary. Finally, in the farthest sectors of the marsh, the water table varies in the order of 1 to 2 cm in relation to tidal flow, caused by the hydraulic and mechanical effect previously mentioned. Sudden rises in the water table only occur during extraordinary high tides close to 2.5 m that can flood the most distal sectors of the marsh. Later, the water table remains constant because of the low permeability of the sediments that hinder groundwater discharge. In both sectors of the marsh, rainfall does not seem to affect groundwater dynamics since there are no variations in the levels coinciding with the days when rainfall is registered. Similarly, if the long-term records between periods of deficit and surplus are analysed, they do not vary either. This could be explained by the fact that superficial clay sediments in the marsh do not favour rainwater infiltration. In general terms, groundwater flow rates and patterns in marshes are controlled by tidal fluctuations, evapotranspiration, precipitation, discharge from adjacent freshwater uplands, and the geometry and hydraulic properties of the marsh sediments. Of these factors, tidal fluctuations are the most widely important driver for groundwater exchange (Wilson and Morris 2012). Thus, the controls derived from precipitation tend to be negligible compared to those originated from tidal action (O'Connor and Moffett 2015).

The results obtained in this work show how the geological-geomorphological controls are key factors for understanding groundwater dynamics and surface water - groundwater interaction, in this particular wetland and also in many wetlands worldwide (Winter 1999; Larocque et al. 2016; Carol et al. 2020; Scheffel and Young 2021). Additionally, it is evidenced that there are different interactions between the landscape units of the wetland. While the ancient tidal flat and the beach ridge plain show strong dependence on climatic conditions, the marsh is mostly subjected to the tidal flow. The landscape units that depend on climate are conditioned by the local water balance and, their hydrodynamics can be affected by changes in the rainfall regime both seasonal and those associated with climate change (Tosi et al. 2013). Within the marsh, hydrological interactions are substantially complex, in relation to periodic changes caused by tidal fluctuations, as it is observed in many coastal wetlands (Winter et al. 1998; Yuan and Lin 2009; Gao et al. 2010; Carol et al. 2012; Alvarez et al. 2015). Note that the beach ridge plain unit is not strictly a wetland, since the water table is located deeper than 1 m and there is no water accumulation on the surface most of the year. However, this unit participates in wetland water flow exchanges. During deficit periods this unit receives groundwater inputs from the ancient tidal flat and contributes to the marsh, while during surplus periods it contributes both towards the marsh and the ancient tidal flat (Fig. 8).

Understanding water dynamics that sustain the different wetland landscape units allow us to identify the factors that can modify the wetland hydrology and consequently its ecosystem functions. Although the Parque Costero del Sur Biosphere Reserve is under UNESCO's MAB program, it

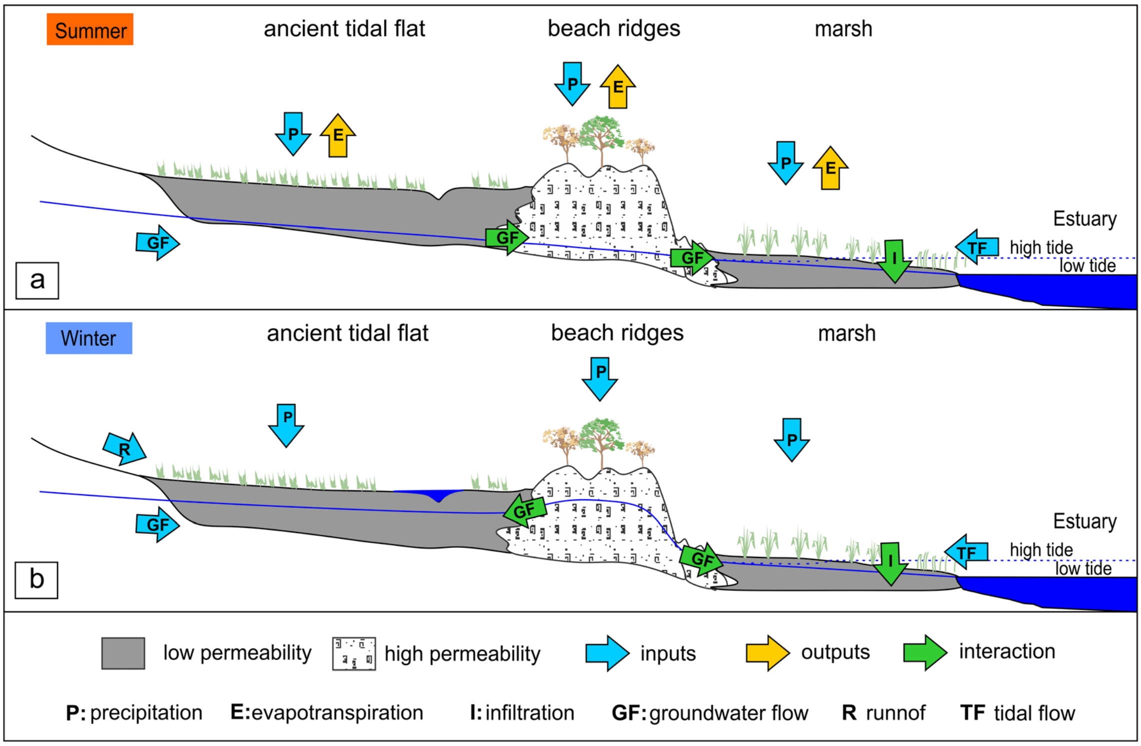


Fig. 8 Hydrological functioning schemes and water exchanges between the landscape units of the coastal plain in the Parque Costero del Sur biosphere reserve. Situations contemplated for the summer (**a**) and winter (**b**) periods

does not correspond to a strict reserve, hence part of it is urbanized. Among the environmental hazards that put this wetland at risk, it can be mentioned the strong coastline retreat occurred during the last decades affecting large sectors of the wetland, with average rates of 3.6 m y^{-1} (Cellone et al. 2016). Shoreline changes produced by both natural and anthropogenic causes (e.g, land reclamation, variation in erosion/deposition rates) alter the natural conditions of wetlands and may produce changes in the interactions between surface water and groundwater, negatively impacting the integrity of coastal wetlands (Liu et al. 2020). Based on land cover changes and the expansion of the urban area, growing exploitation of the phreatic aquifer is expected during the next decades (Cellone et al. 2018), which might have negative impacts on surface-groundwater exchanges and consequently on the different wetland environments. Limestone mining constitutes a threat that seriously jeopardizes the wetland (Carol et al. 2015; Tanjal et al. 2017). It is estimated that 22.6% of the area which was originally occupied by the beach ridges has been exploited during the last century (Cellone 2019). This indirectly affects the wetland, since the modification of the natural topography in this landscape unit alters the natural dynamics of both groundwater and surface water (Carol et al. 2015).

Conclusions

Water dynamics in the Parque Costero del Sur biosphere reserve wetland responds to different geological-geomorphological and climatic controls. Water inlets and outlets, and the flow exchanges vary according to the landscape unit analysed. Three main units were recognized: beach ridge plain, marsh, and ancient tidal flat. The beach ridge plain acts as a preferential recharge area and water entries to the system during winter and spring, causing a periodic reverse flow that contributes both to the marsh and the ancient tidal flat. The marsh is the only unit where groundwater dynamics are controlled by the tidal influence of the estuary. During extraordinary high tides, the marsh is flooded, producing an inflow of tidal water. The lower permeability of the surface sediments, both in the marsh and in the ancient tidal flat, determines that there is no recharge from precipitation or water inlets by surface runoff. In general, during summer, the water table tends to decrease due to the higher evapotranspiration and water deficits, which determine that there is no water entry into the system coming from rainfall. The analysis carried out in this work highlights the environmental and climatic factors that condition water dynamics, as well as its temporal and spatial variations. Furthermore, this study provides basic information for future surveys to be carried out in the area and for the generation of a water resource management plan aimed to guarantee the wetland sustainability and the preservation of the diverse environments that comprise it.

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 and Universidad Nacional de La Plata (National University of La Plata) for financially supporting this study by means of their grants PICT2013–2248 and N782. Further, we wish to thank to Punta Indio local government for their valuable collaboration.

Availability of Data and Material Data are available with the corresponding author and will be provided upon reasonable request.

Code Availability 'Not applicable'.

Authors' Contributions FAC: conceived of the presented idea, did the fieldwork, analysed the data, and wrote the manuscript. GB: performed the NDMI and participated in the fieldwork. LS, CT, EV: participated in the fieldwork. EC supervised the project and wrote the manuscript. All authors discussed the results, provided critical feedback, and helped shape the research. All authors read and approved the final manuscript.

Funding PICT2013–2248 grant Agencia Nacional de Promoción Científica y Tecnológica (National Agency for Scientific and Technological Promotion) N782 grant Universidad Nacional de La Plata (National University of La Plata).

Declarations

Conflict of Interest/ Competing Interests There is no conflict of interest / competing interest.

Ethics Approval Not applicable.

Consent to Participate All authors gave their consent to participate.

Consent for Publication All authors gave their consent to publish this work in Wetlands.

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