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A retrospective assessment of the hydrological conditions of the Samborombón coastland (Argentina)

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ABSTRACT

Coastal wetlands are transitional zones that play an important role as buffers between the land and sea in several ways, such as protecting the land from storm surge and reducing the input of nutrients from surrounding watersheds to the sea. Understanding the influence of human activities on the hydrological conditions of coastal wetlands is of paramount importance for preserving the ecological function and biodiversity of these unique ecosystems. In the last century, the Samborombón coastland (Argentina), which is an extensive intertidal wetland, has been affected by hydraulic projects and human activities. In this study, through a retrospective assessment of the hydrologic conditions, we show the impacts of channelization, embankments and mining on the surficial and groundwater hydrology of the Samborombón wetlands. The results indicate that channelization has promoted tidal flooding and seawater encroachment along the channels. The embankments have separated large areas from the estuary tides; during heavy rainfalls, they act as obstacles and cause the inundation of inland regions while allowing the accumulation of sodium chloride by saltwater evaporation after tidal overtopping events. The freshwater resources in the aquifer of the paleo-coastlines have been seriously damaged by mining of the shell ridges. The halophyl vegetation in the marshlands and the native forest of the shell ridges, which depend on tidal flow and fresh water, respectively, have been threatened. Nevertheless, although the hydrology of the Samborombón coastland has undergone changes, the engineering projects did not permanently modify or damage the surrounding ecosystems. The outcomes of this study will be useful for remediating ecosystems that have been impacted by human activities by following the fundamentals of ecological engineering.

1. Introduction

Coastal wetlands are highly dynamic environments that act as transitional areas between the land and the sea and are governed by continental and marine processes. Estuarine wetlands are exposed to frequent natural fluctuations and alterations. They are periodically inundated by high tides and storm surges as well as being flooded during intense rainfall. In coastal wetlands, marine and continental waters are exchanged and surface water and groundwater are mixed to form complex spatially and temporally variable systems (e.g., Tóth, 1963; Werner and Lockington, 2006; Robinson et al., 2007; Wolanski, 2007; Cao et al., 2012; Werner et al., 2013). Groundwater seeps from the land to the sea and seawater intrudes into coastal aquifers. In estuarine wetlands, the mixing of seawater and groundwater depends on the regional geo-morphologic characteristics of the coast, including ground elevation, soil texture, subsoil heterogeneity and climatic conditions (e.g., Sophocleous, 2002; Rizzetto et al., 2003; Pousa et al., 2007; Teatini et al., 2011; Braga et al., 2013a,b; Day et al., 2013). Hydrological processes in such areas are often highly influenced by human activities, such as the overexploitation of natural resources, land reclamation, hydraulic projects and urbanization. These processes hasten salt contamination, land degradation, pollution and subsidence, which cause serious damage to soils and freshwater resources and threaten the ecological system. For example, urbanization, industry and port activities have greatly affected the environmental quality of Santos Bay (Brazil), resulting in severe sediment contamination and water pollution (Zanardi Lamardo et al., 2000; Abessa et al., 2005; Magalhães et al., 2012). In the Yangtze River Estuary (China), engineering projects, such as the construction of a

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dam and a deep-water navigation canal, have caused many hydrodynamic modifications (Yang et al., 2005; Tang et al., 2011; Zhang et al., 2013), while urban development and industrial growth have caused the deterioration of surface water quality (Ren et al., 2003). The Han River Estuary (South Korea) has undergone changes in water dynamics and chemistry due to engineering projects, such as the construction of submerged dams (e.g., the Singok and Han River dams), which have significantly decreased freshwater outflow to the open sea (Park, 2004; Yoon and Woo, 2013). In the northern Adriatic coast of Italy, the overexploitation of subsurface fluids during the 20th century, especially during the 1960s and 1970s, was responsible for regional subsidence. The decrease of ground elevation produced a significant retreat of the coastline, erosion of salt marshes and tidal flats, increased the frequency of flooding in lowlands and historical cities such as Venice and Ravenna (Carbognin and Tosi, 2002; Amos et al., 2010 and references therein) and worsened the saltwater contamination of shallow aquifers and farmlands (e.g., Carbognin et al., 2009; Viezzoli et al., 2010).

Understanding the influence of humans on the hydrologic conditions of transitional coastal environments is of paramount importance because of the widely recognized buffering functions of these unique transitional ecosystems for biodiversity and valuable economical resources such as agriculture and fisheries. This issue is also essential for planning the correct restoration of ecosystems that have been substantially disturbed by human activities and for guiding environmental adaptation in a changing climate. In this sense, ecological engineering, which is defined as the design of sustainable ecosystems that integrate human society with the natural environment for the benefit of both, has to be developed (Mitsch, 2012; Cheong et al., 2013).

Samborombón Bay, which is an extensive intertidal wetland that was declared a RAMSAR site in 1997, is located on the Argentinean side of the outer estuary of the Rio de la Plata (Fig. 1). The bay extends for 180 km (224,000 ha) and receives the Samborombón River from the northwest, the Salado River from the west and the Ajo River from the south. Lowlands and marshlands are present behind extensive salt marshes and muddy tidal flats. They are frequently flooded by tides and storm surges from the Atlantic Ocean, but the most significant damage to socio-economic development often results from heavy rain on the coastal plain. For this reason, several natural and artificial canals have been constructed to drain the bay's low hinterland.

The world's major estuarine wetlands are subject to economic development and social transformations that exert great pressure to exploit natural ecosystems and trigger changes in the hydrodynamics and hydrochemistry of the water resources. Unlike many of the world's estuaries that are heavily populated and industrialized, Samborombón Bay contains only small urban and built-up areas. The socio-economic development is mainly associated with livestock farming and mining. Nevertheless, several engineering and hydraulic projects have been constructed over the last century without assessing the anthropogenic impact on the hydrology of the coastal wetlands. The hydrological studies that have been carried out in the area have focused on the aquatic communities of the Río Salado basin (e.g., Conzonno et al., 2001; Gabellone et al., 2008; Rosso, 2008), estuary dynamics (e.g., Guerrero et al., 1997; Simionato et al., 2004; Acha et al., 2008), the hydrodynamics and hydrochemistry of the surface and groundwater (e.g., Carol et al., 2009, 2011, 2012; Carol and Kruse, 2012) and the present and expected hydro-morphologic setting in relation to relative sea level rise (Tosi et al., 2013). To date, no studies have integrated the previous natural surface and subsurface hydrology and analyzed the effect of human interventions at both regional and local scales. The retrospective assessment of hydrologic conditions is a methodology that conceptualizes the surficial water and groundwater interactions that are driven by natural conditions and human-induced processes. The results of studies of site-specific processes can successfully be extended to a larger scale to characterize the hydrological setting of the entire coastland. The retrospective assessment of hydrologic conditions requires the identification, compilation and analysis of relevant existing data sets. Remotely sensed data provide a synoptic view of the terrestrial landscape and can be especially useful for assessing and monitoring natural resources (e.g., surface water, vegetation, wetlands) over large areas with frequent regular observations (Jiang et al., 2008, 2013; Sleeter et al., 2013). Satellite images represent a unique means of evaluating long-term changes in climate and hydrology over wide and inaccessible areas that lack in situ measurements. Images provide support to regional hydrological studies because they reveal patterns, land cover and land use modifications (Campbell, 1996). Moreover, they can provide reliable information about the extent and spatial distribution of "hot spot" events (i.e., floods due to rivers, storm surges or intense rainfall). The systematic archiving of Landsat data makes this information valuable for retrospective analyses of environmental characteristics that are applicable to regional studies (Wulder et al., 2012).

The overall aim of this work is to develop a conceptual model of the hydrologic setting of the Samborombón coastland under natural conditions, such as those at the beginning of the last century, and modified by anthropogenic interventions. The model was developed by a retrospective assessment of the hydrological conditions that was aided by the interpretation of satellite images that were integrated with the results of previous studies and observations from exploratory field investigations.

2. Materials and methods

2.1. Study site description

The coastland of Samborombón Bay (Fig. 1) is part of the Río de la Plata estuary and is influenced by the estuary's semidiurnal microtidal regime (Acha et al., 2008). The tidal wedge penetrates from the Atlantic Ocean into the upstream portion of the estuary with salinities that vary from 20 to 1 g/L at the outer and upper limits, respectively (Guerrero et al., 1997).

The climate is humid temperate with an average annual rainfall of 940 mm and evapotranspiration rates reach 770 mm/yr (Pousa et al., 2011). Several studies and historical records describe significant climatic oscillations that are evidenced by alternating periods of droughts and floods (Olivier, 1959). Moncaut (1957a) reported that during the "gran seca de Darwin" (1827–1832), the Samborombón and Salado Rivers dried and were filled with dead animals, while Moncaut (1957b) described a boat that arrived at the Chascomús lagoon from the estuary (100 km inland) because the entire coast was flooded.

In the last 40 years, precipitation has increased to more than 1000 mm/yr (Kruse and Laurencena, 2005) and the frequency of severe flood events has increased (Scarpati et al., 2011). During the rainy periods, the low slope of the terrain favors the retention of water on the floodplain for long periods, forming shallow lakes and marshes, and the region undergoes prolonged flooding events that can affect part or all of the bay. When this occurs, small towns are isolated, roads are covered with water and crops are damaged.

The fluvial network that flows into Samborombón Bay comprises the Samborombón River (Río Samborombón), the Salado River (Río Salado) and the Ajó River (Río Ajó) (Fig. 1). The Samborombón River and the Salado River flow through an extensive flat floodplain with numerous meanders, most of which are abandoned, and are partially connected to permanent and seasonal

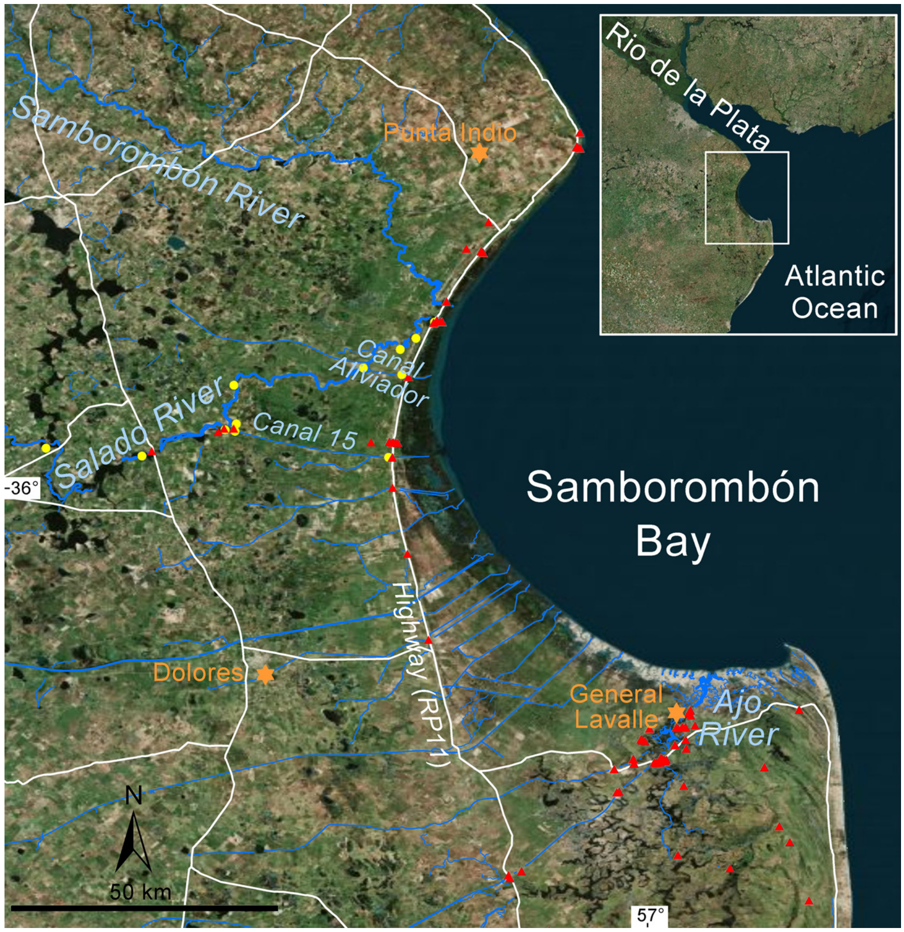

Fig. 1. Satellite image of the Samborombón coastland. The Rio de la Plata estuary is shown in the inset. The main roads and water courses are shown in white and blue, respectively. The stations of the regional monitoring network are indicated with red triangles; the yellow dots represent the monitoring sites from Conzonno et al. (2001). The white stars indicate the National Meteorological Service stations. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

lagoons. The Salado River drains a vast region in the east-central plain of the Province of Buenos Aires that extends over more than 90,000 km^2. The Samborombón River is bordered by flatlands that cover an area of approximately 10,000 km^2, whereas the Ajó River is a limited watercourse that drains the coastal plain and the marshlands in the southern part of the bay.

The control of major floods has required the construction of important hydraulic projects. Since the great flood of 1884, many studies have analyzed how to drain excess water into Samborombón Bay. Two different methods have been proposed: an engineering approach that is focused on channelization and a more natural approach that retains excess water in lowland areas for use during droughts. The latter approach was pioneered by Ameghino (1884), who disagreed with the construction of drainage channels. However, because runoff from the mainland inundates large areas of the Samborombón coast, several channelization projects have been constructed (Fig. 1), such as the Nystromer, Waldorp and Mercau projects (Posadas, 1934). Channels 1, 2, 5, 7, 9, 11, 15 and 16 were constructed within the Nystromer Project. For example, Channel 15 diverts more than 70% of the water of the Salado River from its natural meandering course and discharges it into the Rio de la Plata estuary. Despite the scale of the hydraulic projects, the channelization plan did not completely eliminate severe flooding during heavy rainfall events.

The rivers and canals receive the discharge of phreatic water due to the shallow water table and to the low topographic slope, which is on the order of 10^{-4} in the littoral zone. During heavy precipitation events, the low regional gradient leads to the retention of rainwater for long periods and the water table often rises to the surface. Consequently, the rainwater cannot infiltrate and remains on the soil surface, thereby increasing the flood potential as well as the extents of lakes, ponds and surface impoundments (Scarpati et al., 2011). At high tide, the estuary encroaches on the watercourses; due to the low height of the plain (between 1 and 5 m above sea level (asl)), the tidal surge intrusion propagates toward the continent as much as 7 km in the central region, whereas it may penetrate more than 20 km along the surface watercourses in the southern region. During extreme high tides or storm events, the seawater inflow from the estuary toward the mainland is even higher and floods the marshland (e.g., Tosi et al., 2013). The salinity of the water in the rivers depends on the precipitation, groundwater discharge and tidal inflows, while the salinity of the tidal inflows varies spatially depending on the salinity gradient in the estuary of the Rio de la Plata.

Information about the hydro-morpho-geologic setting of Samborombón Bay has been reported in several studies (e.g., Carol et al., 2009, 2011, 2012; Carol and Kruse, 2012; Tosi et al., 2013) and is summarized in Fig. 2. The hydrodynamic and hydrochemical behaviors of shallow groundwater are influenced by the geomorphological characteristics of the coastland. The coastland is composed of the silty soil plain (not considered in this study), silty-clay coastlands and marshlands (Fig. 2a). The latter includes salt

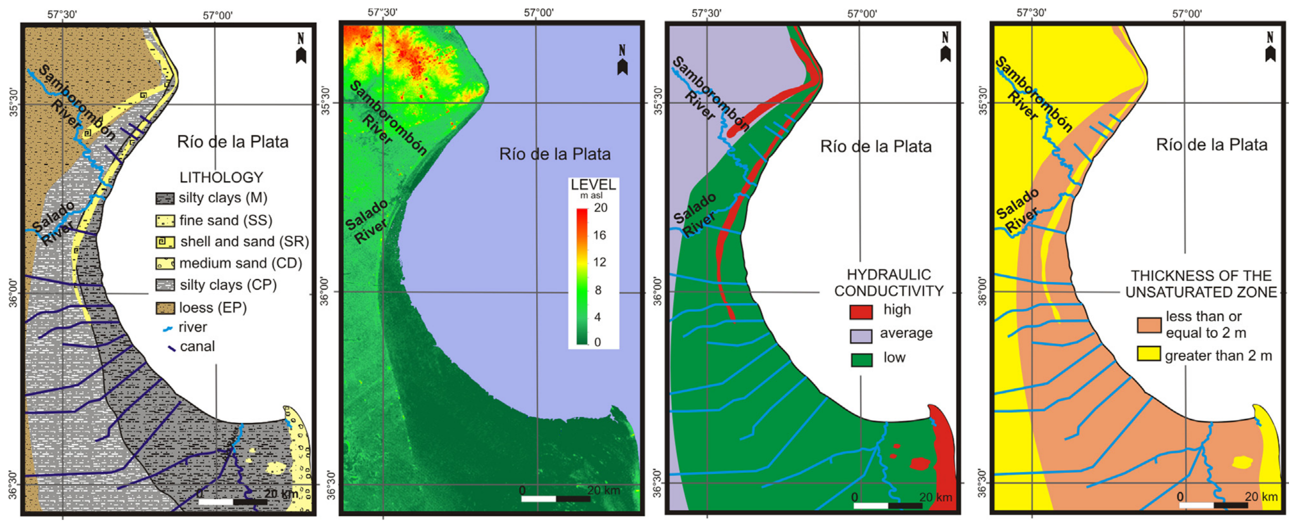

Fig. 2. Thematic maps of the study area: (a) main geomorphological units; (b) digital elevation model (DEM) obtained with Shuttle Radar Topography Mission (SRTM) data; (c) qualitative map of the hydraulic conductivity of the surficial sediments; (d) map of the thickness of the unsaturated zone.

marshes and tidal flats. The coastal plain has an average elevation of 3 m asl and is composed of silty-clay deposits (Fig. 2b). The water table is less than 1 m below the ground surface (Fig. 2d) and seasonal fluctuations of the water table depend on the distribution of precipitation, which is the main source of aquifer recharge. The groundwater discharge flows toward the bay, the drainage network (natural and artificial) and low-lying areas.

The marshlands are approximately 100 m wide at the northern tip of the bay, more than 20 km wide at the southern end (Fig. 1) and have an average height of 1.5 m asl. The marshlands are composed of low permeability silty-clay sediments (Fig. 2c) with shell ridges in the central and northern parts of the bay and patches of small sand sheets in the southern region (Fig. 2a). In the marshes, the level of the water table is mainly regulated by tidal fluctuations. At low tide, groundwater discharge flows toward the bay; at high tide, however, when the water level in the estuary exceeds the regional discharge level, the tidal inflow contributes to the replenishment of groundwater in the marshes. The groundwater in both the coastal plain and marshland is a sodium-chloride type with a salinity that is usually greater than 2 g/L. The salinity of the water in the marshes varies with depth and depends on the tidal cycle (Carol et al., 2009, 2012).

In the southern part of the bay, the expansion of livestock farming toward the marshlands required the construction of embankments across the tidal channels to prevent tidal inflow, which reduced flooding and increased the amount of grazing land. Important changes in the ecohydrologic setting occurred in the areas that were excluded from the tidal cycle (Carol et al., 2013).

The shell ridges, which are present locally in the central and northern portions of the marshlands, are elongated landforms that run parallel to the coastline and are composed of shell remains and sand (Fig. 2a). They are between 50 and 120 m wide, often more than 2 km long and at elevations of 5–12 m asl.

The sand sheets in the southern area reach a maximum elevation of 3 m asl and rarely exceed 200 km^2 in area. Both the shell ridges and the sand sheets are high permeability deposits (Fig. 2c) in which rainwater is stored as fresh groundwater lenses over the denser saline groundwater of the coastal plain. The water table in the shell ridges is at an elevation of 4–5 m asl (Fig. 2d) and fluctuates according to amount of precipitation. The groundwater is a sodium-bicarbonate type with a salinity that ranges from 0.2 to 1.5 g/L (Carol and Kruse, 2012). The sand sheets have similar hydrodynamic and hydrochemical behavior; however, due to their limited extent and thickness, they do not form a significant freshwater reservoir (Carol et al., 2009). The shell ridges have been exploited to extract shells for use in the construction industry since the mid-twentieth century. According to official data from the Mining Division of the Province of Buenos Aires, 144,800 tons of shells and sand were extracted from the Samborombón area in 2002. There are currently more than 10 active quarries in the area. Because the shell ridges are higher than the nearby land, the main roads were established on these geomorphologic features, whereas they were built on raised embankments on the coastal plain and marshlands. The most important highway, the Provincial Highway 11 (Ruta Provincial 11 or RP11), was built between 1932 and 1940. It runs along the entire littoral zone parallel to the coastline. In general, highways and roads cause hydrological alterations to the coastal plain and marshlands that are similar to those caused by the embankments themselves.

2.2. Methodology

To develop conceptual models of the past and present ecohydrological settings of the study area, we used a descriptive approach that is based on the analysis of long time series of satellites images. Existing hydrological–hydrogeological, meteorological, geological and morphological data and information from field surveys were collected and interpreted to map the geomorphologic, permeability and water table characteristics and to provide additional information for the conceptual modeling. Where in situ measurements were lacking, satellite images were used to obtain reliable information about the extent and spatial distribution of hydrologic events. The spatial and spectral resolution of Landsat images makes them highly suitable for detecting land-cover changes and monitoring natural environmental processes. The Landsat images were obtained from the USGS archive of the Earth Resources Observation and Science (EROS) Center (http://glovis.usgs.gov). The satellite images were acquired from the TM and ETM+ sensors on the Landsat 5 and Landsat 7 platforms, respectively (Supplementary data). To aid the interpretation, the images were radiometrically corrected as described in Chander et al. (2009) and geometrically corrected using the ENVI (Exelis Visual Information Solutions, Boulder, CO, USA) image processing software. RGB and NIR band compositions were used for the regional time series analysis. The

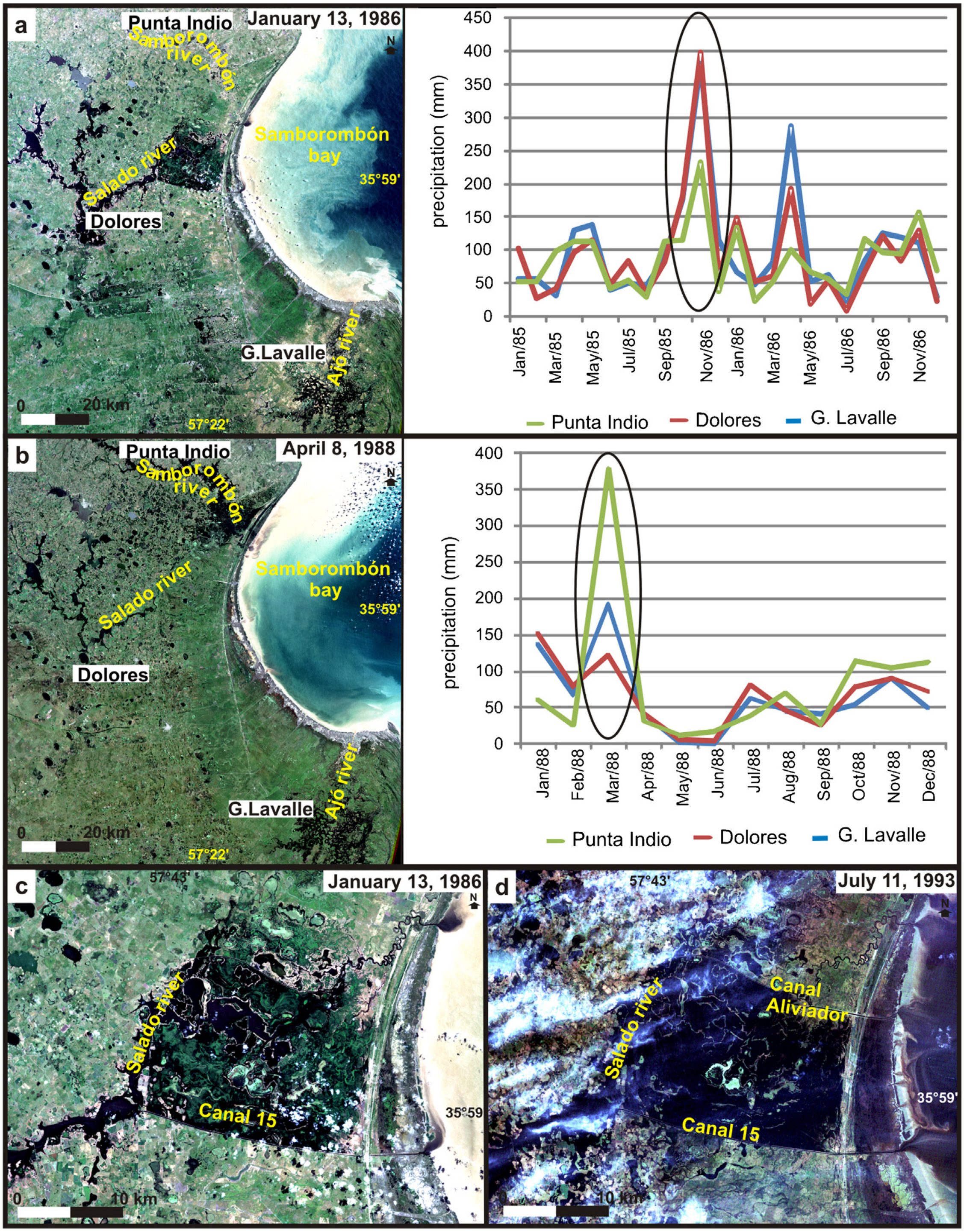

Fig. 3. Flooding of the Samborombón coast. Landsat 5 images and monthly precipitation: (a) the Salado River and Ajó River basin are flooded, while the Samborombón River basin remained drained (January 13, 1986); (b) the Samborombón River basin is flooded, while the Salado Ajó River areas are not flooded (April 8, 1988). Landsat 5 images showing a detail of the lower Salado River basin during rainy periods (c) before and (d) after the construction of the Canal Aliviador (January 13, 1986 and July 11, 1993, respectively).

Landsat images were selected based on two main objectives: (i) to identify the modifications induced by anthropogenic activities and (ii) to highlight the effects of different climate conditions on the hydrological settings on the coastal plain and marshland. To study the flooded areas and to analyze the impact of human activities on the hydro-geomorphological setting, the satellite images were selected based on the precipitation events, tidal level and the sequence of hydraulic and engineering projects.

A regional monitoring network that is representative of the variable geographic and hydrogeologic setting of the Samborombón Bay coastland was designed to collect groundwater and surface water samples from the main watercourses and canals (Fig. 1). The groundwater monitoring stations include 3-m-deep hand-dug wells and 10-m-deep wells located near windmills. Water samples were collected at low tide to measure the concentrations of major ions in the water column. To analyze the tidal influence on the

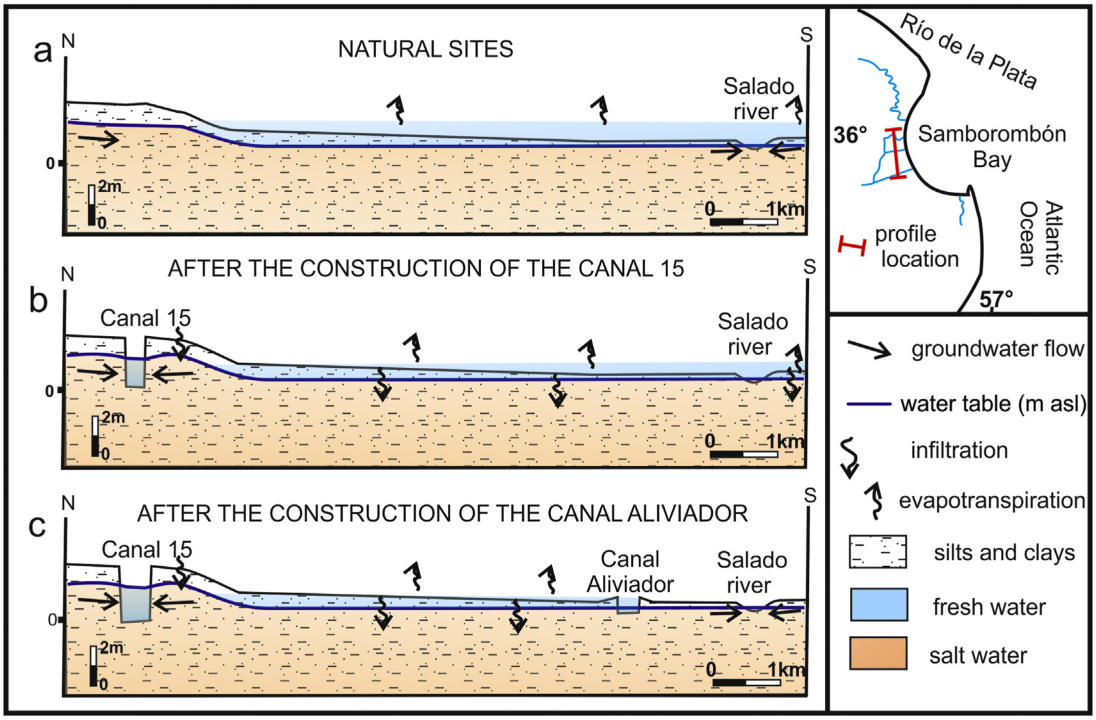

Fig. 4. Hydrologic sketches showing the transition from the previous natural setting to the present-day conditions that are impacted by channelization.

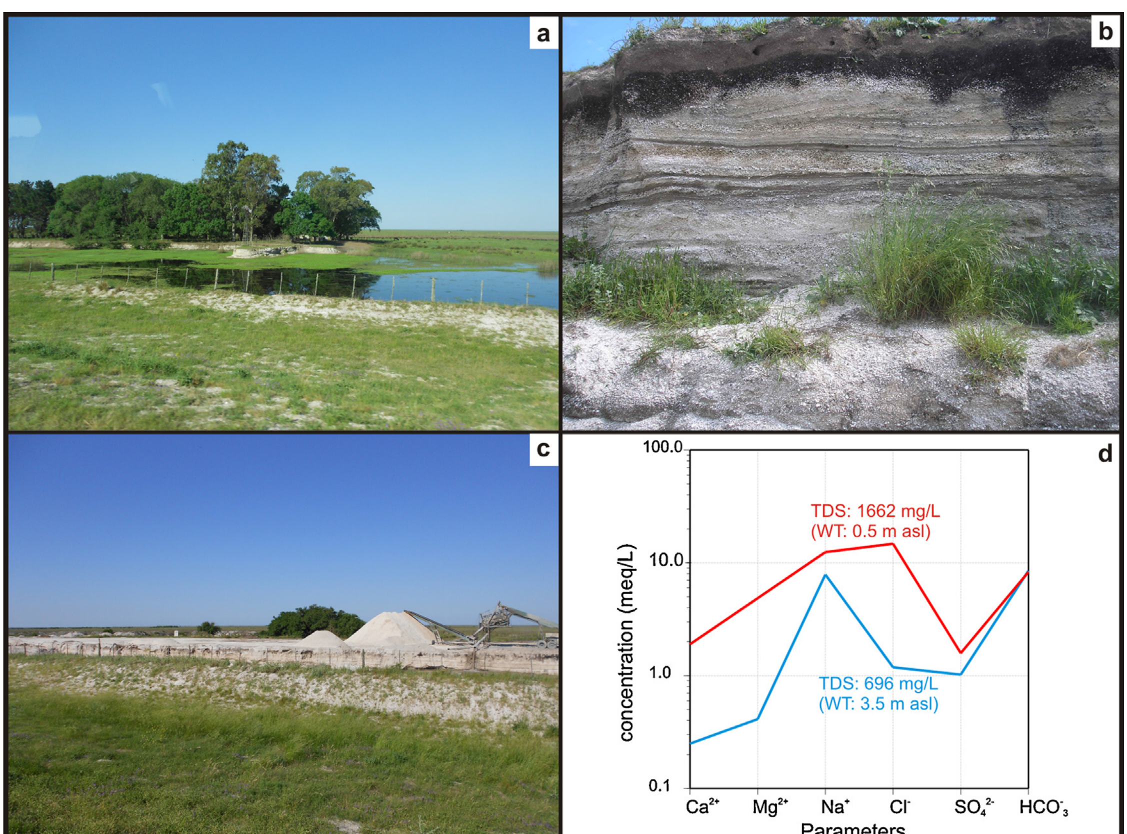

Fig. 5. Photos of shell ridge mining: (a) the level of mining is below the water table; (b) the lateral wall of the shell ridge after excavation; (c) a view of an operational quarry. (d) Schoeller plot of groundwater summarizing the changes of groundwater characteristics; WT = water table and TDS = total dissolved solids.

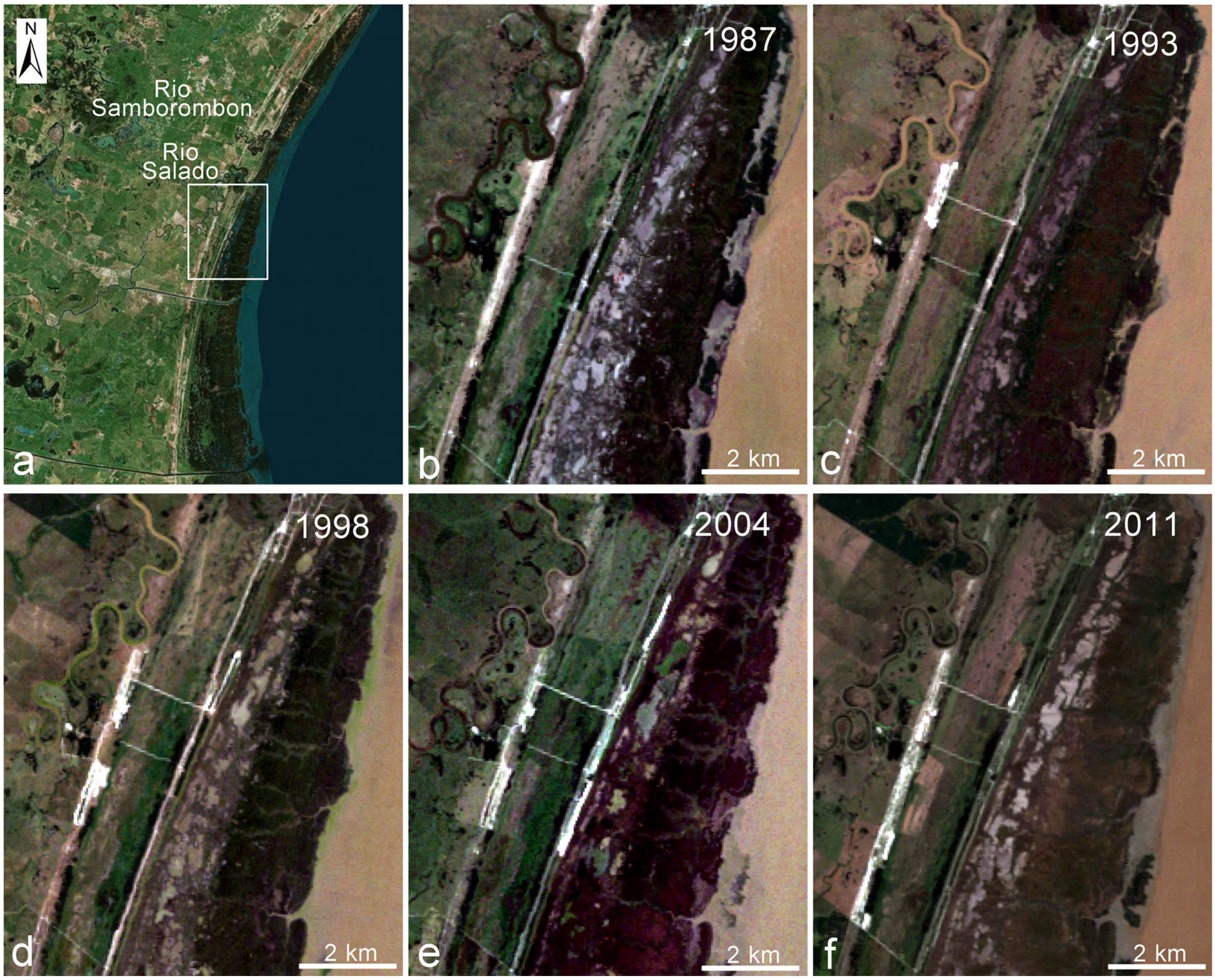

Fig. 6. Landsat 5 images showing the exploitation of shell ridges: (a) site of the quarry between the Salado and Samborombón Rivers; (b) in 1987, extensive work in the quarry area has caused the disappearance of *Celtis tala* on the shell ridge; (c) in 1993, part of the quarry area is abandoned and has been partly revegetated with grasses from saline environments and partly covered by artificial ponds; (d) in 1998, the quarry has been reactivated and the vegetation is affected again; the water table is visible in some parts of the quarry area; (e) in 2004, the mining activity continues and the area of the exposed water table has increased; (f) in 2011, the exploitation area has continued to expand.

main rivers, canals and groundwater, the salinity measurements were carried out every 0.50 m depth along the water column with a Solinst TLC manual level measurement device. The water table and water level measurements were performed to define the groundwater flow and the relationship between the surface water and the groundwater. Moreover, Cl^- was analyzed in 20 samples of surficial sediments from marshlands using the EPA9253 method. In addition to the regional monitoring network, we used data derived from previous geological (Violante et al., 2001; Fuck et al., 2010; Richiano et al., 2012) and hydrologic analyses (Conzonno et al., 2001; Fernandez Cirelli and Miretzky, 2004; Dapeña and Panarello, 2004), especially in the western part of Salado River basin, where monitoring sites are scarce.

Monthly rainfall data from 1900 to 2012 were provided by the National Meteorological Service-SMN. The meteorological stations (Punta Indio, Dolores and General Lavalle) were selected because they were representative of the study area. Daily tidal data from the port of General Lavalle were also analyzed.

3. Results

The retrospective analysis focused on the ecohydrological responses to the human activities at regional and local scales. The main anthropogenic modifications to the hydrological processes are due to (i) channelization, such as the excavation of drainage channels, (ii) mining of the shell ridges, and (iii) construction of embankments, such as dykes, tide embankments and roads.

3.1. Channelization

The construction and modification of drainage canals in the lower Salado River basin can be documented by the analysis of satellite images beginning in the late 1970s. Moreover, some of the largest recent floods along the Samborombón coastland were detected by satellite images.

The Landsat image acquired in January 1986 (Fig. 3a) shows that the central and southern parts of the littoral zone are completely flooded as a result of extreme precipitation; approximately 400 mm of rainfall was recorded at the Dolores and General Lavalle stations in November 1985 in the Salado and Ajo river basins (Fig. 3b). In contrast, there are no flooded areas in the northern region because much less precipitation fell in the Samborombón River basin (e.g., 230 mm at the Punta Indio station). A different event occurred in March 1988. The monthly rainfall at Punta Indio was 380 mm (the lower portion of the Samborombón River basin), while at Dolores

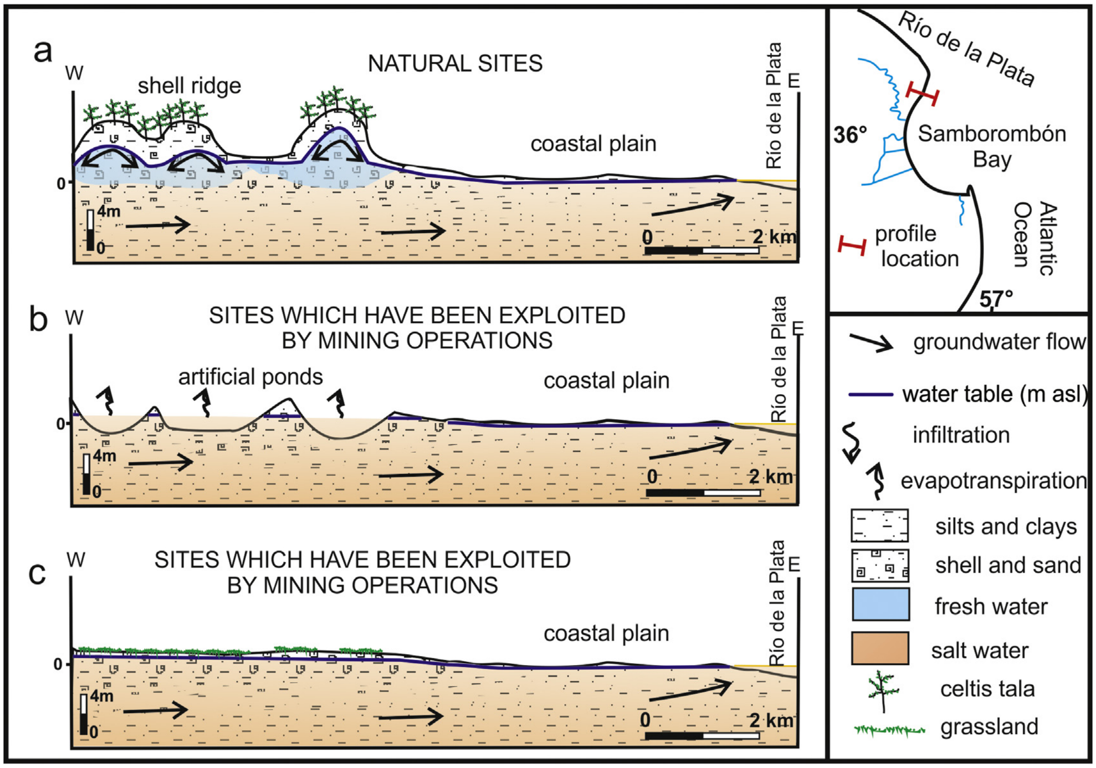

Fig. 7. Hydrologic sketches showing the shift from the natural setting to the present-day conditions that are impacted by exploitation of the shell ridges.

and at General Lavalle it was less than 200 mm. This caused serious flooding in the northeastern area but no flooding in the southern and central regions (the lower part of the Salado River basin); this event was captured in the Landsat image acquired on April 1988 (Fig. 3c and d).

The satellite image acquired on 13 January, 1986, approximately three months after the extreme precipitation events of November 1985, indicates that Canal 15 did not mitigate the effects of the prolonged flooding (Fig. 3e). To address this problem, the Canal Aliviador was constructed in 1987 to intercept the Salado River downstream from Canal 15. Nevertheless, subsequent satellite images show that the Canal Aliviador was not able to handle the drainage. The satellite image acquired in July 1993 (Fig. 3f) shows that most of the area was still flooded during the major rainy period.

The conceptual hydrological model of the lower basins of the Salado and Samborombón Rivers, in the central part of the coast, is shown in Fig. 4. Fig. 4a shows the situation at the beginning of the last century. These areas were naturally prone to flooding because of their hydro-morphologic characteristics and the overlapping effects of storm surges, shallow water table, heavy local and regional rainfall. This region is emblematic of the hydrological modifications caused by the channelization. Fig. 4b shows the situation during very rainy periods after the construction of the canals (e.g., Canal 15), which are not able to drain the excess water, resulting in flooding of the area between the river and the channel. Some of the runoff infiltrates into the aquifer and slightly decreases the salinity of the groundwater, while some evaporates. The construction of the Aliviador Canal in 1987 partially mitigated the flooding of the bay and prevents a narrow strip of land between it and the Rio Salado from being inundated (Fig. 4c). Canal 15 was widened and deepened in 1997 and now transports water not only in periods of flooding but also under normal conditions.

3.2. Mining of shell ridges

In the central and northern areas of the coast, the mining of shell ridges began in the mid-twentieth century and is still in progress. Field investigations demonstrated that the ridges are excavated to the elevation of the adjacent coastal plain and occasionally below the water table, which leads to the formation of ponds in the abandoned quarries. The extraction process includes the removal of vegetation cover and in some cases the removal of the sand. The water used to separate the sand from the shells is withdrawn from the lens-shaped freshwater aquifers, which is the only source of high-quality water suitable for human use in the area (Fig. 5). The mining activity has a significant impact on the groundwater; it causes salt contamination and lowers the water table, leading to the disappearance of the freshwater lenses. The mining activity causes a significant increase in the Ca^{2+}, Mg^{2+} and Cl^- concentrations as well as the total dissolved solids of the groundwater (Fig. 5d). These ions characterize the coastal plain and the increased concentrations are evidence of the increased salinity in this environment. Meanwhile, the HCO_3^- and Na^+ concentrations are stable because HCO_3^- is in equilibrium with atmospheric $CO_{2(g)}$ and Na^+ dominates both environments. The temporal analysis of the satellite images shows the impact of the mining on the native vegetation of the wetland. The *Celtis tala* forest, which is only developed on the shell ridges, is cleared at the beginning of the mining operation and the vegetation recovery is based on grasses from the adjacent coastal plain. A quarry is shown in the satellite image acquired in 1987 (Fig. 6a), in which the white color corresponds to an excavation that exposes shell deposits. The narrow, dark green strip adjacent to the shell ridge is a strip of *Celtis tala* shrubs, which is a remnant of the forest that covered the shell ridge before mining. The satellite image acquired in 2003 (Fig. 6b) shows that several years after mining operations ceased, the quarry area was partially revegetated by grasses from the adjacent coastal plain (medium green shades) and

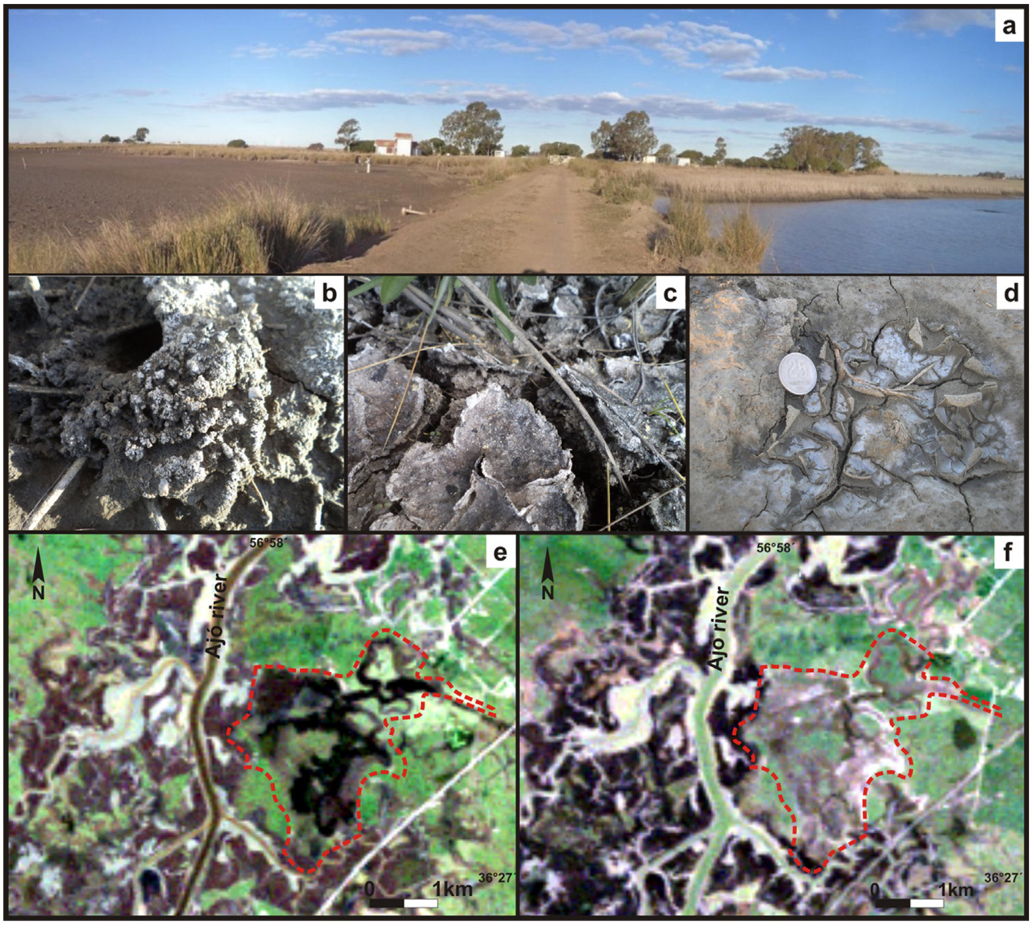

Fig. 8. (a) Photo of an embankment (in the center) that separates part of the marshes from the tidal cycle (on the left). (b–d) Photos of salt precipitates on the surface of the marshes. Landsat images of a marsh area adjacent to the Ajó River during: (e) a wet period with rainwater accumulation and (f) a dry period; the images were acquired on September 13, 1987 and October 1, 2011, respectively. The dotted line indicates a portion of the marsh area that is separated from the tidal cycle by the embankments.

partially covered by ponds that formed as a result of the outcropping of the water table (black color). The satellite images acquired in 2010 (Fig. 6c) show that quarrying had resumed; this is shown by the exposed shell outcrops (white color) and the disappearance of some of the grasslands and the remnants of the *Celtis tala* forest.

Fig. 7 shows the evolution of the freshwater lenses from their natural location in the ridges to the disappearance of the entire fresh water reserve due to mining. Under natural conditions, the positive relief landforms of the shell ridges, which are composed of high permeability sands, allow the storage of rainwater that infiltrates and forms local lens-shaped freshwater aquifers above the regional saline groundwater (Fig. 7a). Ponds form in sites that are excavated below the water table and the saline water of the coastal plain discharges into them (Fig. 7b). Where the excavations do not reach the water table, the quarry becomes a transit area for groundwater with subsequent inflow of saline water from the coastal plain (Fig. 7c). In both cases, the most significant environmental impacts are the elimination of the only sources of drinking water in the region and the loss of the native *Celtis tala* forest. When the quarries are abandoned, the meadow vegetation from the adjacent coastal plain gradually revegetates these areas.

3.3. Embankments

The southern coast is the most hydrologically impacted region because of the restriction of tides due to the construction of embankments. The satellite images from 1986 and 2011 show that 80% of the altered areas were already separated from the tidal cycle

Table 1
Examples of salinity values of surface water and groundwater in natural marshland and in marshland that is separated from the tidal cycle by the embankments. WS: water sampling; LT and HT: low and high tides, respectively.

	Salinity marsh surface water (mg/L)			Salinity marsh groundwater (mg/L)	
	Surface	Bottom of the riverbed		Surface	To 1 m depth
Natural marsh					
LT (−1.24 m asl)	8645	17,940	LT (0.52 m asl)	6500	12,025
HT (1.06 m asl)	16,705	19,435	HT (0.74 m asl)	9980	14,040
Marshland excluded from the tidal cycle by the embankments					
LT (0.54 m asl)	5648	5650	LT (0.65 m asl)	7215	7220
HT (0.54 m asl)	5645	5650	HT (0.65 m asl)	7215	7218

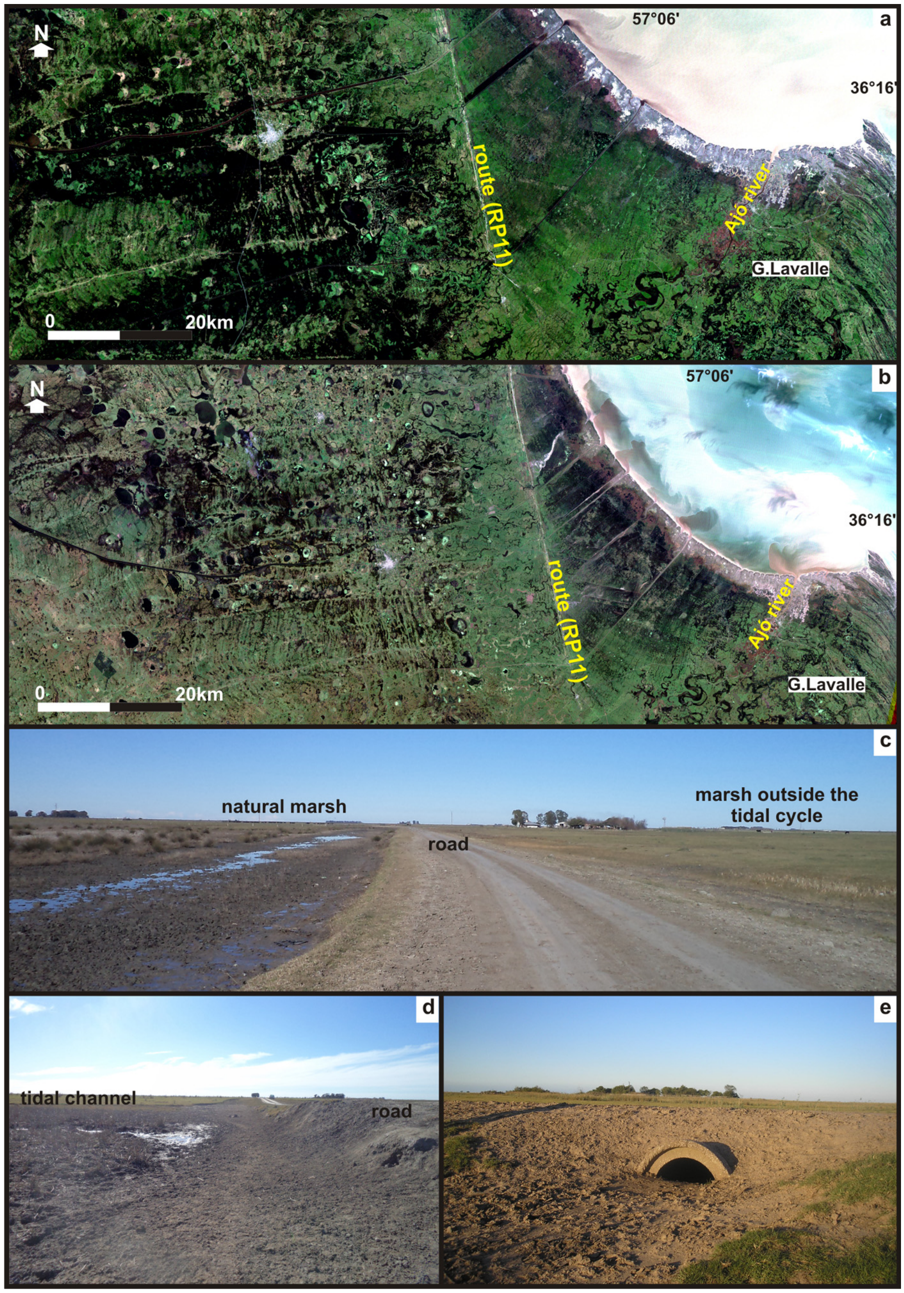

Fig. 9. Image of the highway that crosses the central-southern area of the marshlands showing how the highway acts as a hydraulic barrier. The Landsat 5 images show the highway (a) blocking the drainage of excess water toward the estuary during a rainy period and (b) limiting the propagation of seawater toward the coastal plain during an extreme storm surge event. Photos of the marshlands show: (c) a secondary road lacking culverts that impedes the tidal inflow (on the right of the photo); (d) a tidal channel intersected by a road without a drainage system; (e) a road with obstructed culverts.

by 1986, which caused important changes in the hydrologic setting and the environment of the marshlands (Fig. 8).

Unlike the natural hydrological setting, which is characterized by layers of different groundwater salinities, the marshland that is separated from the tidal cycle by the embankments does not show variations in salinity in the water column. Table 1 shows salinity values of surface water and groundwater in marshlands that are affected by tides and that are blocked from the tidal cycle by embankments. During very high tide events, overtopping of the embankments occurs. In the poorly drained marshlands, evaporation predominates and leads to an accumulation of sodium chloride (halite), which is clearly visible by the emergence of precipitated salt on the soil surface (Fig. 8a–d). In poorly drained marshlands, the amount of Cl^- detected in surface sediments is as high as 15,775 mg/kg (Table 2). Although embankments efficiently prevent tidal inflow, they have a significant impact on the hydrology during heavy rainfall events because rainwater accumulates in the marshland that is segregated from the estuary (Fig. 8e and f). The rainwater forms pools in the marshlands that are confined by embankments and remains for several weeks. During this time, the rainwater dilutes the salts in the groundwater and in the soil, decreasing the chloride concentration in the surficial sediment to 1252 mg/kg (Table 2). Finally, the natural salt marsh sediments have average chloride concentrations of approximately 5000 mg/kg. These marshlands are inhabited by a crab population and vegetation that depend on the tidal flow (*Spartina alterniflora*,

Table 2
Maximum, minimum and average Cl^- values (mg/kg) in surficial sediment in the marsh areas subjected to tidal cycles and areas where tides are blocked by the embankments.

	Surficial sediment in natural marsh Cl^- (mg/kg)	Surficial sediment in marshland excluded from the tidal cycle by the embankments Cl^- (mg/kg)	
		With drains	Without drains
Average	5128	2485	12,070
Maximum	6300	3962	15,775
Minimum	3148	1252	7905

Spartina densiflora, *Salicornia ambigua*, *Juncus acutus* and *Zizaniopsis bonariensis*). When the marsh is blocked from the tidal cycle, the crab population does not develop and the native plant species are replaced by salt-tolerant grasses of the adjacent coastal plain.

The construction of roads and highways modified the continental runoff and groundwater flow toward the bay and tidal inflows because they act as barriers that block the coastal plain from the tidal cycle and worsen flooding during heavy rainfall events. Culverts are placed along the roadway to manage the runoff from the road surface and groundwater flow toward the bay. However, the Landsat image acquired on June 10, 2002 during a period of a mean monthly rainfall of approximately 300 mm (Fig. 9a) clearly shows that the culverts are inadequate and form a barrier rather than a system to drain excess water to the bay.

In contrast, in the image taken on April 22, 1993 (Fig. 9b), the highway stops the propagation of seawater toward the coastal plain during an extreme storm surge event, in which the sea level was higher than 2 m asl.

Although internal roads are minor structures, they cause significant changes at the local scale. In the field surveys performed since 2006, it has been observed that in large portions of the marsh, internal roads cut across the tidal channels and restrict tidal flow to parts of the marsh (Fig. 9c).

Fig. 10 shows the marshlands of the central-southern part of the bay, where the construction of embankments has influenced the ecohydrologic conditions. Fig. 10a and b shows hydrogeologic cross-sections of the natural marshes at low tide and high tide, respectively. Fig. 10c and d, which represents the effects of the embankments on the marshes, outlines two environments with different hydrodynamics, hydrochemistry and vegetation. To the east, the marshlands are encroached by the tidal flow and maintain the natural saline stratification of both the surficial water and the groundwater, while the western region is excluded from the tidal cycle and the native vegetation is modified (Fig. 10c). Moreover, the marshes that are blocked from the tidal flow are generally flooded during heavy rainfall because the embankments block the drainage to the bay (Fig. 10d).

3.4. Regional hydrological model

The retrospective assessment of the hydrological conditions using historical time series of remote sensing data and ground measurements of hydrodynamic and hydrochemical variables yields a conceptual hydrological model of the Samborombón coastland. Starting from local investigations of representative areas based primarily on in situ data, the regional models were expanded to the regional scale using satellite data to overcome the lack of ground data in some areas and for some time periods.

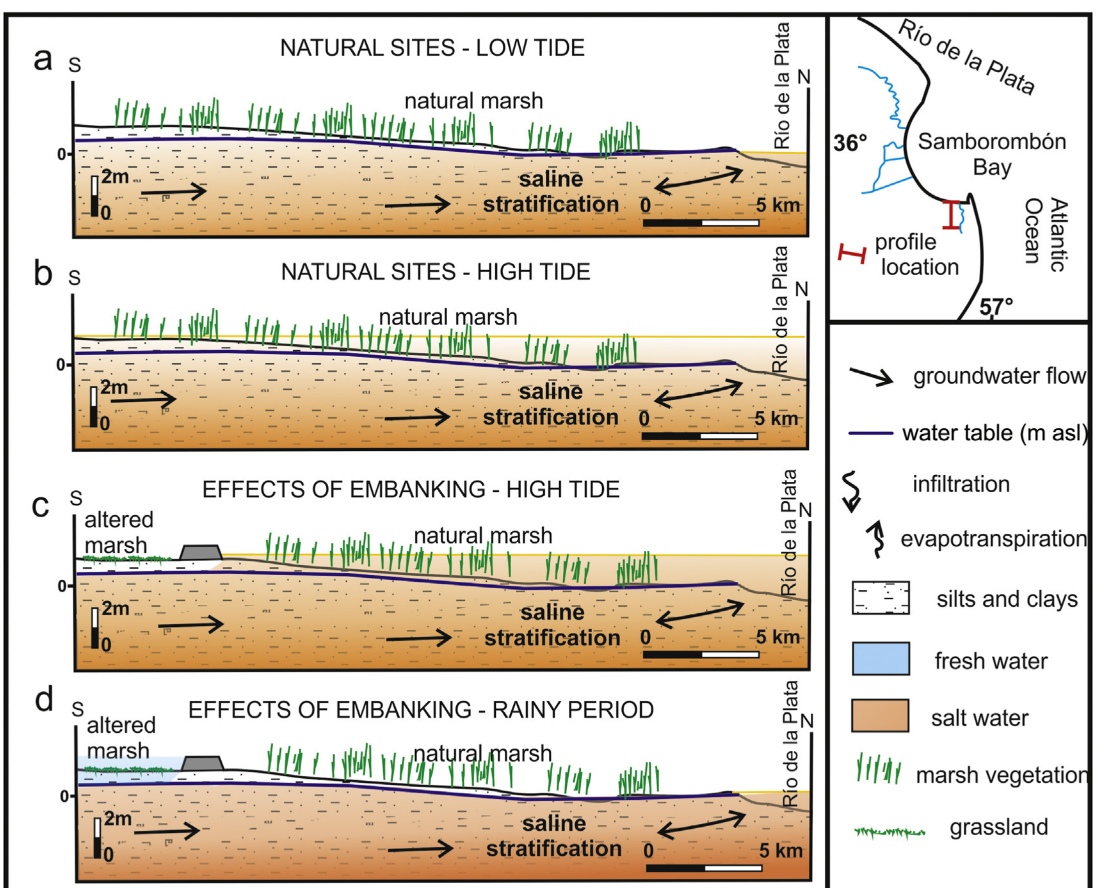

Fig. 10. Hydrologic sketches outlining the transition from the natural setting to the present-day conditions that are impacted by the construction of embankments.

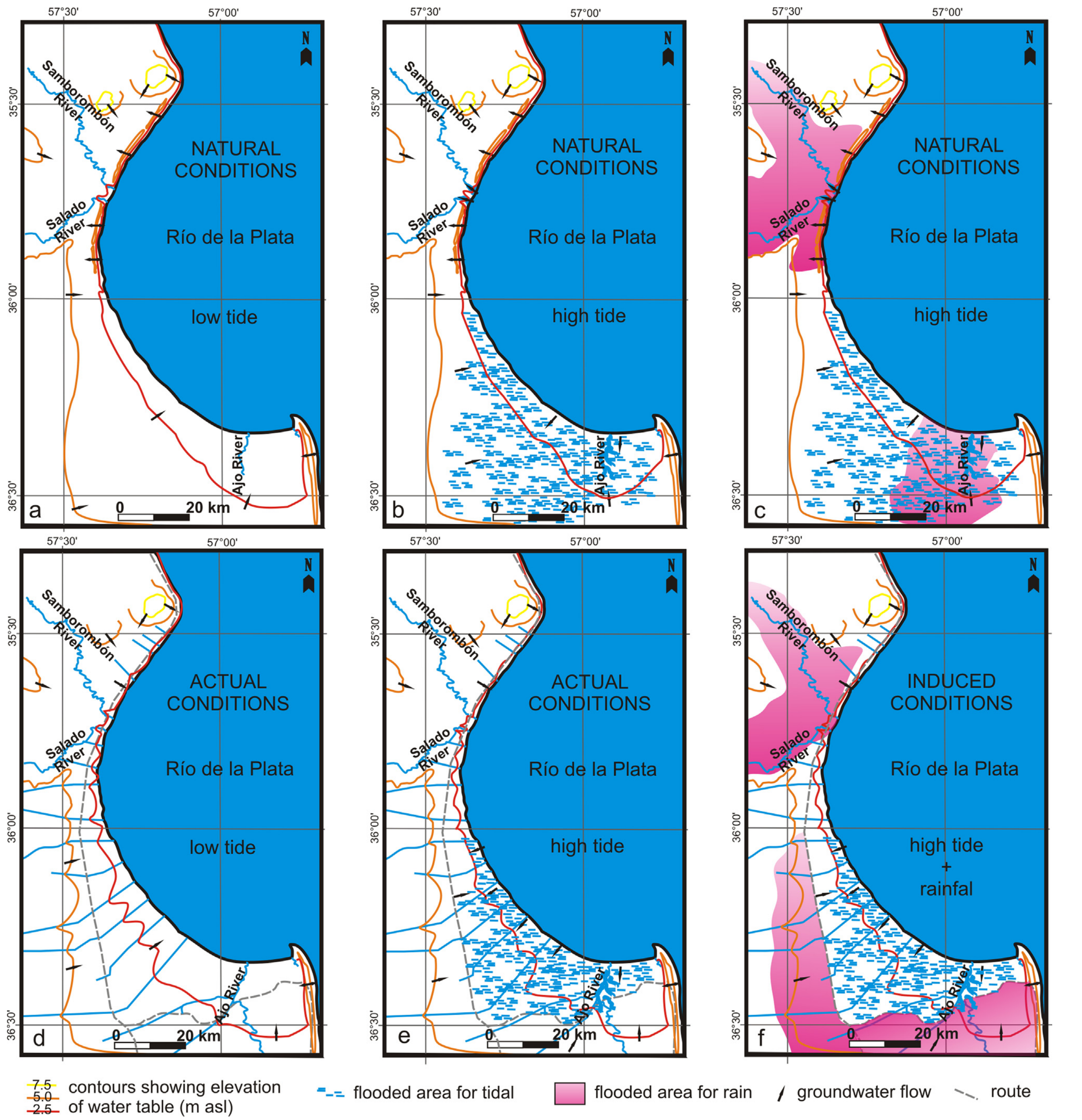

Fig. 11. Model of the groundwater flow and the water table along the Samborombón coast. (a–c) Past natural conditions and (d–f) present-day human-induced conditions; (a) and (d) are during low tide; (b) and (e) are during high tide; (c) and (f) are during heavy rainfall and high tide events.

The upper Samborombón coastal plain is a discharge area that is characterized by a mean groundwater level of approximately 5 m asl, which is approximately 6 m below the ground surface. The water table slopes to sea level at a gradient of 10^{-4} and is close to the ground surface in the lower coastal plain (Fig. 11a). The littoral zone is dominated by low-permeability surface sediments associated with coastal plain and marsh environments (Fig. 2). The water table is less than 2 m deep and the hydraulic gradients of both the surface water and groundwater are extremely low. These characteristics, combined with the humid climate and the tidal influence, make the entire littoral zone highly sensitive to flooding during rainy periods despite the channelization.

Fig. 11a–c and d and f show the regional hydrologic settings of the coastal plain under natural conditions in the past and as affected by humans, respectively. Under natural conditions, the Samborombón, Salado and Ajo Rivers adequately drained the surficial water and groundwater into the bay during low tides (Fig. 11a). The shell ridges received water inflow from precipitation and the water table of the lens-shaped groundwater aquifer was approximately 5 m asl and 2–3 m below the ground surface. Because of the geomorphologic setting, the fresh water that accumulated over the coastal plain was not affected by the tidal hydrology of the estuary and the flow of groundwater from the shell ridges toward the estuary and the plain (Fig. 11a). During high tide, the groundwater flowed from the estuary to the marshlands. The estuary water flowed through tidal channels and the river mouths and recharged the shallow aquifer of the lower coastal plain (Fig. 11b). The marshlands in the lower streams of the natural courses of the Samborombón, Salado and Ajo Rivers and in the nearby tidal channels were flooded (Fig. 11b). Extensive areas of the coast were flooded during extreme rainfall events and severe storms. The flooding of large areas was also facilitated by the long duration of high tides, the shallow water table, which was often naturally exposed in the wetlands, and the lowland setting of the coast (Fig. 11c). Anthropogenic actions altered the natural ecohydrological setting of the coastland and modified the exchange of surface water and groundwater, the ecosystems and the landscape. The channel network at low tide favors the drainage of the coastal plain and the groundwater flows into the bay (Fig. 11d). Conversely, estuary water encroaches along channels and supplies the aquifer during high tides (Fig. 11e). The mining of shell ridges has considerably decreased the recharge areas where rainfall accumulates forms freshwater lenses over the saline groundwater of the coastal plain (Fig. 11d and e). Mining has caused permanent changes in the hydrology, landscape and ecosystems. The construction of roads has restricted the natural intertidal domain (Fig. 11e). The roads act as obstacles for both tidal propagation and the discharge of surface water into the bay. This new hydrologic setting caused an increase in flooding, especially during severe storms and high tides, during which the entire coastland can be flooded (Fig. 11f).

4. Discussion and conclusion

Hydrological changes due to channelization, mining and embankments have been reported in many wetlands around the world (Middleton, 1999; Simenstad et al., 2006). Several extensive stream channelization projects have been constructed to control flooding due to heavy rainfall and to reclaim land for agriculture and urbanization. Channelization typically includes deepening and widening the river beds and straightening the river by cutting off meanders. It increases both the surficial flow and groundwater drainage capacity and decreases the areas of flooding (Shankman, 1996). However, channelization causes faster surficial-groundwater flow and decreases the storage of fresh water that spreads across the coastal plain during dry periods (Brookes, 1988). This negatively impacts the local hydrology and decreases the habitats, biodiversity and nutrient cycling in adjacent areas (Hupp et al., 2009).

The flow of seawater to coastal wetlands has been restricted by the construction of embankments, such as roads and railways, flood protection structures and agricultural projects (Roman et al., 1984; Montague et al., 1987; Mitsch and Gosselink, 1993; Portnoy, 1999; Teal and Weinstein, 2002; Weishar et al., 2005). Embankments cause long-term modifications of the water table, the salinity of upstream marshes and the composition, structure and chemistry of the sediment. This has led to biogeochemical processes such as subsidence and the transition to either freshwater wetland or terrestrial plant communities.

The mining of shell ridges is less common because of their peculiar geological distribution; however, several studies have demonstrated that it has caused the deterioration of local water resources in sensitive environments (Maliva et al., 2010) and the decline of native freshwater-dependent vegetation (Xie et al., 2012).

These types of engineering projects have been constructed along the Samborombón coast and have affected the ecohydrology of the marshland in different ways. Our study demonstrates that the anthropogenic interventions performed over the last century to improve the hydraulic processes and to increase land use have modified the ecohydrology of the Samborombón coastland. The channel network reduced flooding events but modified the exchange of surficial water and groundwater because of the enhanced propagation of the estuarine salt/fresh waters during high tides. The embankments allowed the construction of roads and restricted some of the marshlands while forming drained areas for livestock farming. Where the embankments efficiently block the estuarine regime, the vegetation that depends on the tidal flow died out and was replaced by grazing vegetation. Shell mining reduced the capability of storing rainfall in the aquifers of the shell ridges, which represent the only fresh groundwater resources in the coastland for drinking. In addition, the native forest that grows on the shell ridges because of the freshwater has largely disappeared.

To manage and safeguard Samborombón Bay, several projects have been considered to mitigate the negative impacts of the structures and restore the natural environment, especially after extreme flooding events or dry periods (e.g., MOP, 1956; Saravia et al., 1987). The most recent proposed project is the Plan Maestro Integral de la Cuenca del Río Salado (Halcrow, 1999), which includes both non-structural and structural mitigation measures and also suggests the use of additional drainage projects that are currently under construction.

This study can support the planners and the decision-makers in the management of Samborombón Bay because it examines the evolution of the hydrological setting at a regional level. For instance, this study can be used to provide recommendations for the development of a comprehensive flood hazard plan to address the hazards and risks to the community and minimize exposure. The study can also address mitigation measures by following the fundaments of ecological engineering (e.g., Mitsch, 2012) and contributing to the sustainability of the community and the values and functions of the floodplain, wetlands and other coastal environments. A more holistic approach that integrates the contributions of engineers, geologists and ecologists is required to understand the complex dynamic interrelationships between vegetation, hydrology, hydraulics and the subsurface in wetlands (Zeff, 2011). Moreover, the designation of the Samborombón wetlands as a RAMSAR site in 1997 and the creation of the Reserva Biósfera Punta Indio, the Reserva Natural Rincón de Ajó, the Parque Nacional Campos del Tuyú and the Estación Biológica Punta Rasa have limited the number of engineering projects and have contributed to the preservation of the natural ecosystem and the restoration of affected sites. However, the shell ridges are currently exploited without an environmental sustainability plan from the provincial agencies. Ecological mitigation, compensation and enhancement measures should be mandatory; for example, abandoned mine areas urgently require remediation to reduce the amount of impacted landscape and restore the ecosystem.

Finally, although channelization and tidal restriction have modified the ecohydrology of the Samborombón coast, they have not irreversibly damaged or destroyed the surrounding ecosystems. The modified areas of Samborombón Bay still represent an environment with human and ecological value and have the ability to adapt to change.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ecoleng.2014.03.081.

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