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The hydrologic landscape of the Ajó coastal plain, Argentina: An assessment of human-induced changes

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ABSTRACT

Coastal wetlands rank among the most endangered ecosystems since they are affected by the sea level rise and by anthropogenic activities. The continued loss and degradation of these valuable environments requires greater understanding of groundwater–surface water exchange, as the ecological function of coastal wetlands greatly depends on it. Hydrological research carried out in the lower part of the Samborombón Bay coastland (Río de la Plata estuary, Argentina) by remote sensing revealed the presence of a meandering channel system, which does not appear in modern maps. Analysis of SPOT satellite images and interpretation of historical maps and in situ surveys confirmed that this structure is part of an ancient river system – the palaeo-Rincón de Ajó River – at present almost completely silted up. In addition, multispectral satellite data provided information to develop a conceptual hydrological model, as well as evidence that a significant hydrologic landscape shift occurred due to human-made interventions. The palaeo-Rincón de Ajó River disappeared because water flow in its upper course was intercepted by human-made canals. In its lower course, embankments built for the construction of roads and flood prevention of the wetlands from the Río de la Plata estuary excluded the surface flow from the estuary to the mainland and vice versa. The silting up in the lower course and in the vicinity of the mouth cancelled the original structure of the ancient river.

1. Introduction

Anthropogenic landscapes currently cover most of Earth's land surface. In such environments, human alterations of the surface morphology, ecosystems and processes are significant (Tarolli et al., 2014 and references therein). Coastal systems are arguably the most sensitive areas to the interactions between natural and anthropogenic forces. Nevertheless, achieving a comprehensive understanding of the effect of natural and human-induced processes on coastal plains is a challenge (Chin et al., 2013). All over the world, several coastal wetlands have been dramatically reduced and degraded by climate change and human-induced modifications over time. Climate changes, mostly sea-level rises, cause the progressive flooding of large coastal lowlands, lagoons and deltas, especially where land subsidence is particularly active (e.g., Törnqvist et al., 2008; Syvitski et al., 2009; Nicholls and Cazenave, 2010; Tosi et al., 2010; Teatini et al., 2011; Hallegatte et al., 2013). Moreover, the loss and degradation of coastal wetlands are due to the alteration of their hydrologic setting through major physical interventions (coastal urbanization and agricultural land reclamation) and drastic hydrological regime modifications (large-scale embankments, ditches and drainage channels) (Portnoy and Giblin, 1997; Brinson and Malvárez, 2002; Godet and Thomas, 2013).

Marine and continental surface waters and groundwater flows, as well as physiographic features and climate conditions, interact closely in a coastal hydrologic system. Besides, the structure and ecological function of coastal wetlands greatly depend on tidal flooding and on the freshwater/saltwater exchanges in groundwater and surface water. These properties and processes, which are determinant in species distribution, wetland productivity, and nutrient cycling and availability (Mitsch and Gosselink, 1993), can be conceptualized in a hydrologic-landscape framework (Brinson, 1993; Carol et al., 2011; Alvarez et al., 2015). The concept of

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hydrologic landscapes is based on the idea that the complete hydrologic system interacts with a single, simple physiographic feature, and that this feature becomes the basic building block of all hydrologic landscapes (Winter, 2001). This physiographic feature is a fundamental hydrologic landscape unit, defined on the basis of land-surface slope, hydraulic properties of the soil, geological framework, climatic conditions and water balance (Winter, 2001; Xie et al., 2011; Small and Sousa, 2014). A hydrologic landscape unit has a complete hydrologic system, consisting of surface runoff, groundwater flow and interaction with atmospheric water (Winter, 2001). Besides, it shows indirectly that any variation that may occur in the hydrologic landscape will modify the water flow and the environmental conditions depending on them.

Despite the relevance of this topic, the study of human-induced changes in such environments has generally been approached by means of ecological, geomorphological and sedimentological research, while less attention has been paid to hydrologic landscape changes (Sun et al., 2003; Rizzetto et al., 2003; Portnoy and Giblin, 1997; Xu, 2003; Van Dyke and Wasson, 2005; Tosi et al., 2009; Anthony et al., 2014).

The Ajó coastal plain (Fig. 1), located in the southern littoral of the Samborombón Bay (Argentina), is characterized by the presence of approximately 3000 km^2 of marsh environments covering both the littoral sector of the Río de la Plata estuary and the ancient tidal plain on the mainland. The Ajó coastal plain is a poorly drained, low-lying area, with highly organic clayey soils and the water table near the ground surface, characteristics that lead to

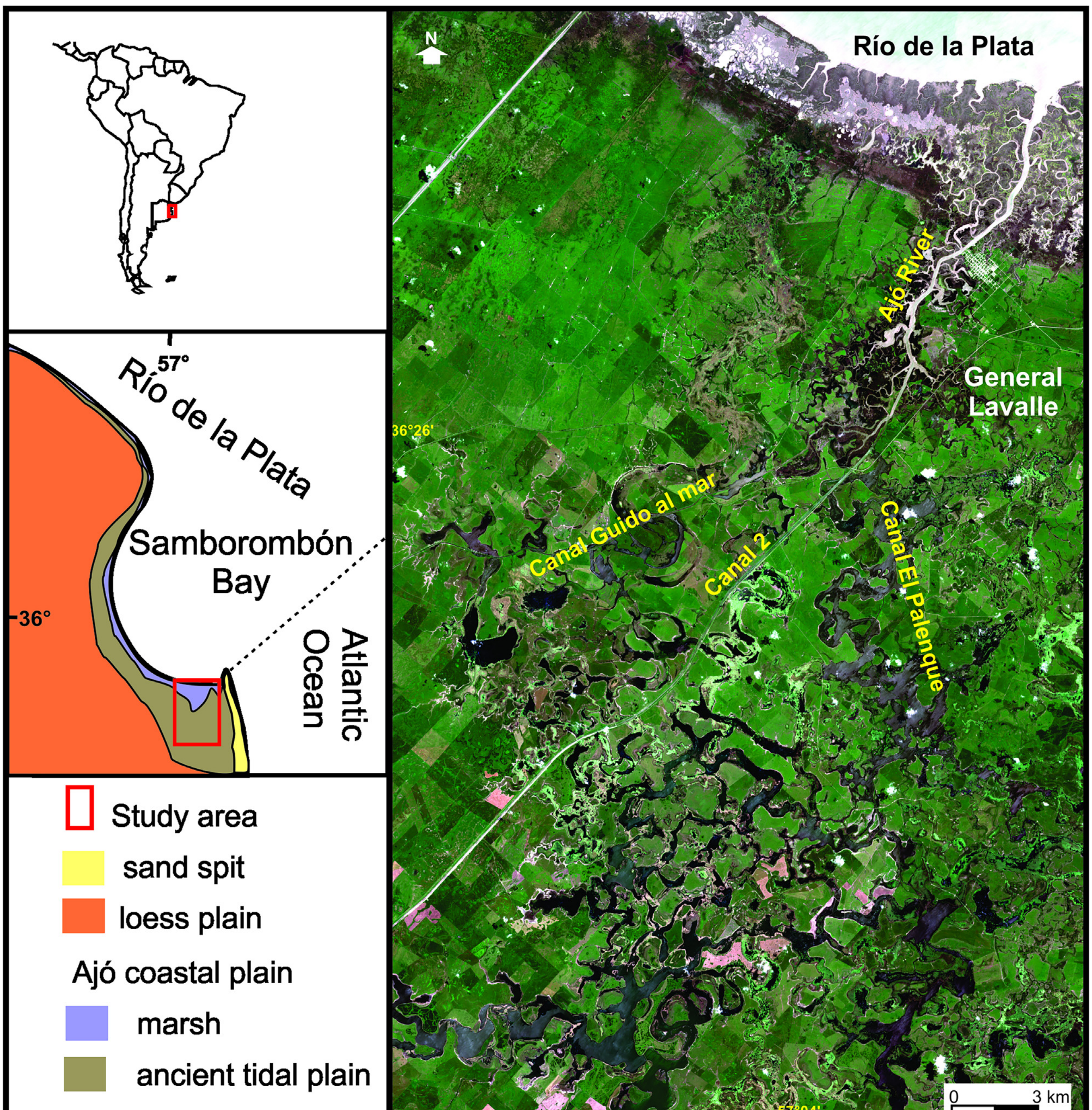

Fig. 1. Location and general setting of the study area. Pseudo-true colour Sentinel-2 image (band combination: R = red, G = green, B = blue).

great floods during the rainy periods and storm surges (Carol et al., 2010). In order to improve the regional drainage, numerous canals have been built since the beginning of the 20th century. In addition, a number of embankments have been built—with a main direction perpendicular to the surface runoff and the groundwater flow—in order to restrict the tidal encroachment in the coastal plain and to allow road traffic in the littoral region. Despite the benefits of these anthropogenic interventions, they significantly altered the natural hydrologic landscape and changed the natural hydrologic setting of the coastland (Carol et al., 2013, 2014). Even though the anthropogenic structures only cover a small area within such a large coastal wetland, they affect surface water–groundwater dynamics at a regional scale.

The objective of this work was to assess how the different engineering works influenced the evolution of the hydrologic landscape in a sector of the Ajó coastal plain. The first step undertaken in this study was to identify the current characteristics of the hydrologic landscape by means of SPOT satellite images, and such features were validated by in situ observations. Second, the ancient drainage system was reconstructed, comparing the current features with geographic and historical topographic maps. Finally, a conceptual model of the evolution of the hydrologic landscape was developed.

2. General setting of the study area

The sea-level oscillations that occurred during the Quaternary gave rise to the formation of an extensive coastal plain on the right bank of the Río de la Plata, whose outer estuary is called the Ajó coastal plain. The geomorphological evolution of this coastal plain is associated with the migration of a sandspit located to the east, which fosters the development of a marsh towards the inner sectors (Fig. 1). Such a migration has been occurring since the beginning of the Holocene and the spit progradation has been accompanied by the advance of the marsh, which ceased to be active as it lost its connection with the tidal flows (Violante et al., 2001). At present, the coastal plain is formed by a marsh that occurs on the littoral of the bay and an ancient tidal plain that covers the south-central sector (Fig. 1). In this tidal plain, the ancient tidal channels can be observed as meandering depressions with a complex drainage.

The climate is humid temperate with a mean annual precipitation of 1078 mm and alternating dry and wet periods. The monthly water balances (Thornthwaite and Mather, 1957), calculated on the basis of historical mean precipitation and temperature data (1909–2012), show that the actual evapotranspiration is 759 mm/year. In the monthly balances, water surpluses can be observed in the winter months (March–October) and deficits in the summer months (November–February) (Carol et al., 2015).

The water table is close to the surface (less than 1 m deep) or it emerges in the depressed areas. Regional groundwater flows from the tidal plain sectors, located on the southern tip of the study area, towards the bay, with a hydraulic gradient below 10^{-3} %. Locally, groundwater tends to discharge into the ancient tidal channels, where the water table emerges in the wet periods (Carol et al., 2015).

The low permeability of the surficial sediments that compose the coastal plain favours the accumulation of rainfall excess, which collects in the ancient tidal channels. In turn, the marsh is periodically flooded by the high tide entering from the estuary, which has a semidiurnal microtidal regime (Carol et al., 2011). At present, the coastal plain area drains to the Ajó River by three canals. The Canal El Palenque collects the water surpluses of the south-central area following the course of the ancient tidal channels, whereas the Canal 2 and Canal Guido al Mar have straight courses and they cross the tidal plain in the western sector, transporting water from the loess plain area located to the southeast (Fig. 1).

The coastal plain is a sparsely populated area that is mainly devoted to livestock farming. On the right bank of the Ajó River, close to the mouth, is the town of General Lavalle, which has a fishing port. At present, the port is not very large; however, towards the end of the 19th century, it was the third most important port in the country, with the export of salted meat being its main activity.

3. Methods

The characteristics of the hydrologic landscape in the coastal plain area were initially defined on the basis of the analysis of satellite images acquired by the French Système Probatoire d'Observation de la Terre (SPOT) taken under different soil moisture, surface water and vegetation conditions. The SPOT-5 images were provided by the Comisión Nacional de Actividades Espaciales (CONAE) in DIMAP format, with geo-referencing information (coordinates of the upper left-hand corner of the image and pixel size) and updated sensor calibration coefficients. Four SPOT-5 images, taken on 30 September 2012, 15 November 2012, 12 February 2013 and 17 June 2013 (around 13:30 UTC), were used. SPOT images consisted of four spectral bands (B1 to B4): bands B1 (green: 0.50–0.59 μm), B2 (red: 0.61–0.68 μm) and B3 (near infrared: 0.78–0.89 μm) had a spatial resolution of 10 m; band B4 (mid-infrared, 1.58–1.75 μm) had a resolution of 20 m and was resampled to 10 m. The spatial resolution of the SPOT images made them highly suitable for mapping land surface properties and monitoring natural environments at a local scale. To aid in the interpretation, the images were radiometrically corrected as described in Pons and Solé-Sugrañes (1994) using the ENVI (Exelis Visual Information Solutions, USA) image processing software. Colour infrared (CIR) band combination was used for the visual identification of the hydrologic landscapes through the detection of areas with different hydrological and ecological properties and the presence of human-made structures.

The normalized difference water index (NDWI) was used to support the assessment of permanent water and flooded areas. The NDWI (McFeeters, 1996) was calculated using the following equation:

$$NDWI = \frac{(Green - NIR)}{(Green + NIR)}$$

Water is highly reflective in the green parts of the spectrum and highly absorptive in the near infrared (NIR) band. The ratio between these spectral bands was used as an indicator of surface water, both permanent and temporary.

The results of the visual interpretation of the different conditions of soil moisture, surface water and vegetation retrieved from the SPOT satellite image dataset, as well as the associated NDWI maps, were compared to identify hydrologic landscapes in a sector of the Ajó coastal plain. Moreover, the surface water in the southern area was classified with the maximum likelihood supervised classification (Richards, 1999). This method calculates the probability that a given pixel belongs to a specific class and then assigns each pixel to the class that had the highest probability.

These images were also used to identify human-induced modifications in drainage and morphology (canals, embankments, routes), which were verified in field surveys. Subsequently, historical maps (Martin de Moussy, 1873; Paz Soldán, 1888; Delachaux, 1893; Estrada, 1904) and topographic charts were compiled to verify the occurrence of drainage palaeoforms in the recent past (last 120 years), as well as to locate in time the engineering works documented in such charts. The original topographic charts were geo-referenced and mosaicked in a GIS environment (ArcGIS – Esri) and converted from the native coordinate system, i.e. Gauss–Krüger (Argentina) – Campo Inchauspe to UTM – WGS84 for the overlay analysis with satellite images.

Sediment samples were collected at depths ranging from 0.1 to 1.6 m in the areas subject to anthropogenic modification. A surface sediment sample was collected from the area currently drained by the Ajó River. Sediment texture was described and samples were washed through a sieve with a mesh opening of 63 μm to eliminate the fine (silt and clay) fraction. The organogenic content was analyzed under the microscope and, in particular, the foraminiferal assemblages were studied to determine the depositional environment. Foraminifera were classified according to the taxonomic order of Loeblich and Tappan (1987). Assemblage composition and presence/absence of benthic foraminifera are used in the study of coastal wetlands to reconstruct the natural evolution or to detect anthropogenic impacts (Benito et al., 2015; Serandrei-Barbero et al., 2011).

Supported by the present-day and historical mapping, satellite imaging and field surveys, a conceptual model of the evolution of the hydrologic landscape was developed at a regional scale, showing the processes that led to the current hydrological situation in response to anthropogenic modifications. The hydrodynamic behaviour and the relationship between surface water and groundwater were described on the basis of data obtained in studies previously undertaken by the working group (Carol et al., 2008, 2009, 2011, 2012, 2015). These studies were based on the periodic monitoring of the surface water (continental and tidal flows) and groundwater levels since 2005 undertaken in different sectors of the coastal plain.

4. Results

4.1. Analysis of current and retrospective hydrologic landscapes by remote sensing

The analysis of satellite images acquired under different soil moisture, surface water and vegetation conditions showed the occurrence of the relict landform of an ancient watercourse on which there is no information and which is not represented in present-day maps (Fig. 2). This relict landform is located to the west of the Ajó River, appearing in the satellite image obtained during a wet period as a parallel watercourse clearly observable in

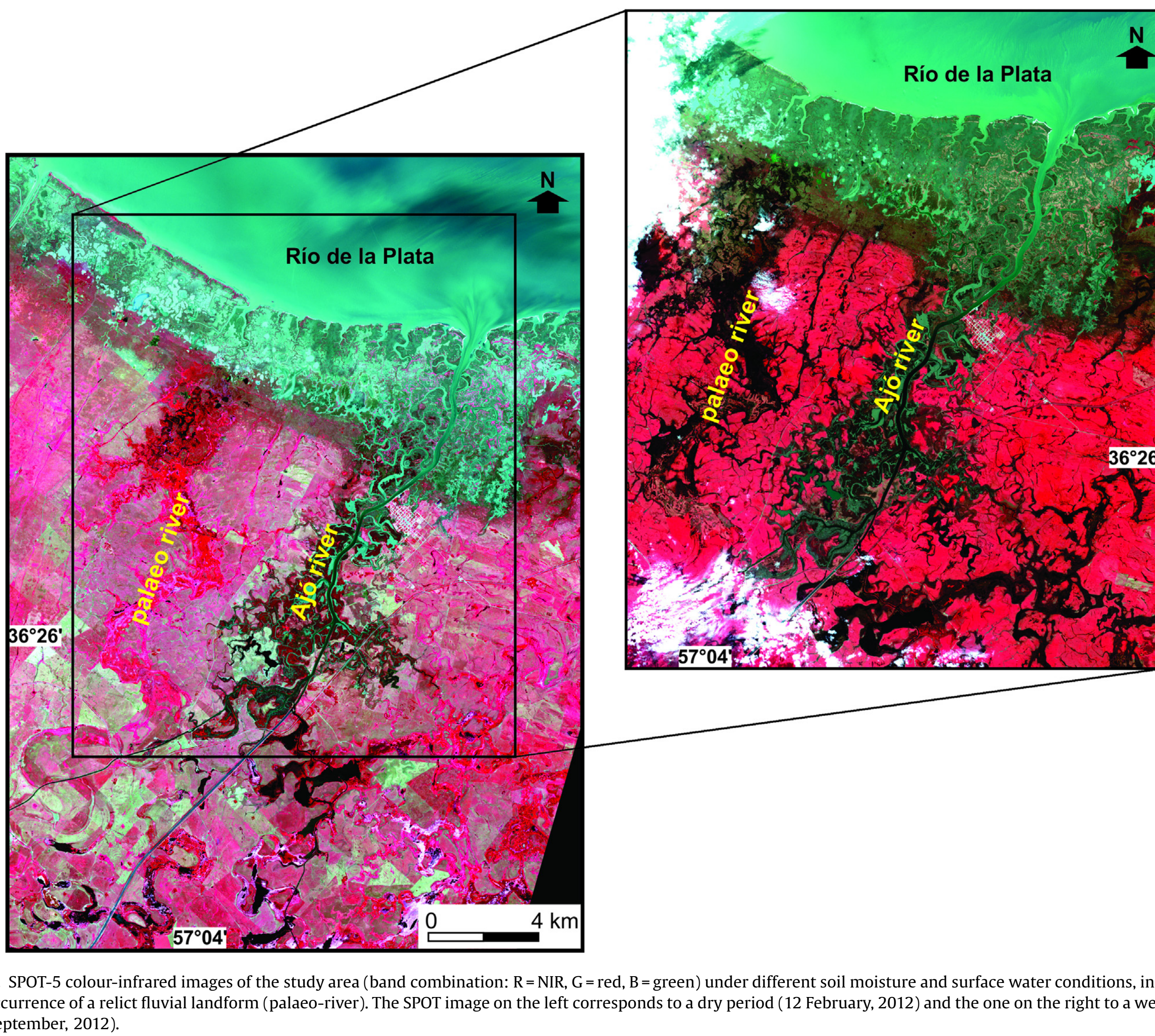

Fig. 2. SPOT-5 colour-infrared images of the study area (band combination: R = NIR, G = red, B = green) under different soil moisture and surface water conditions, indicating the occurrence of a relict fluvial landform (palaeo-river). The SPOT image on the left corresponds to a dry period (12 February, 2012) and the one on the right to a wet period (30 September, 2012).

black, which indicates the occurrence of surface water or saturated soils. This watercourse is indicated in present-day topographic charts as a shrub swamp area (Cañada Rincón de Ajó), which has temporary surface water.

The detailed study of the drainage system, supported by satellite images and topographic survey data, made it possible to observe that in natural conditions—i.e., not taking into consideration the channelizations—the ancient tidal channels were

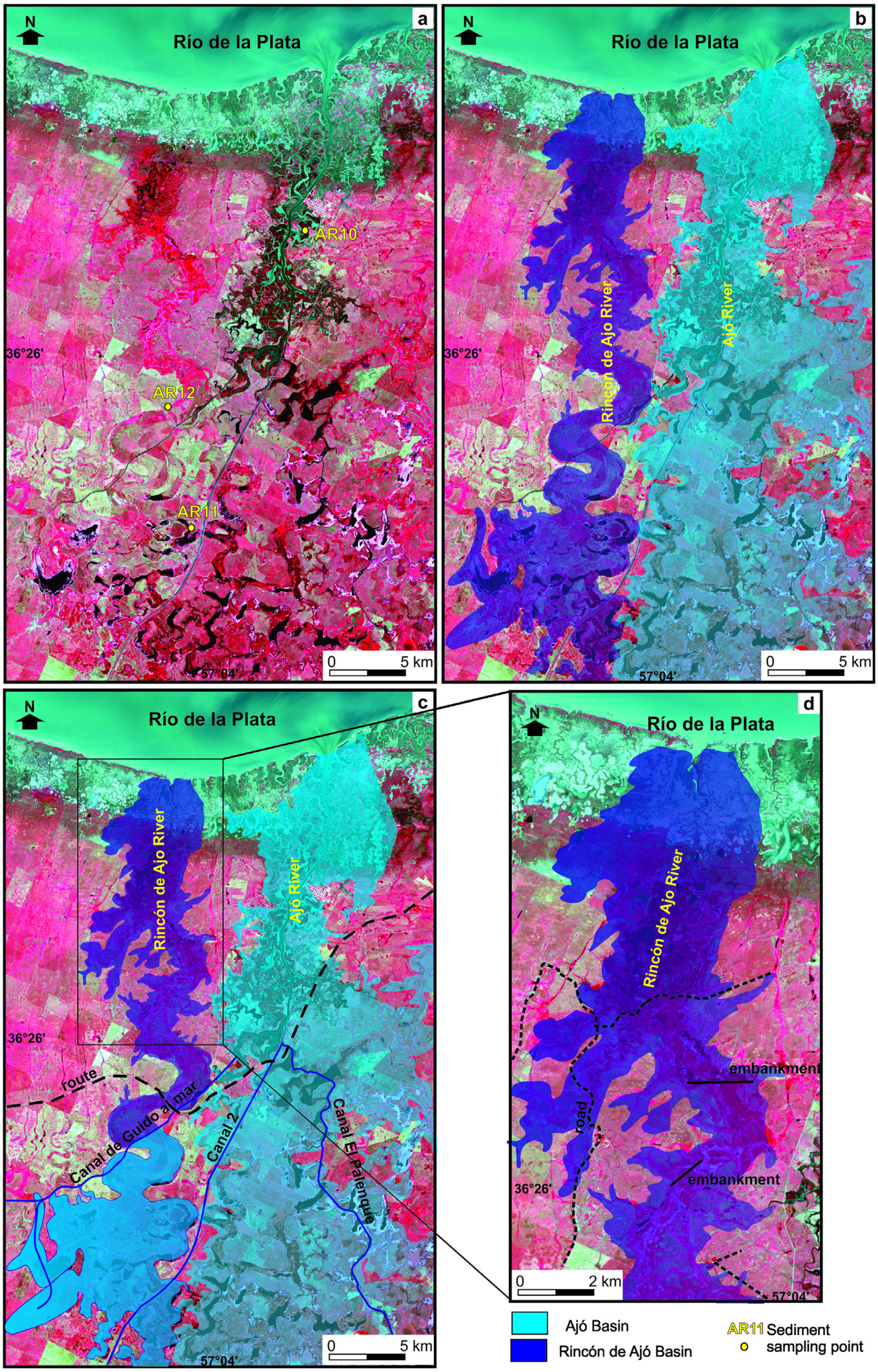

Fig. 3. Natural and human-induced hydrologic landscape: (a, b) characterization of the drainage areas; (c, d) identification of the anthropogenic modifications and interpretation of the changes in the hydrologic landscape. In the background, SPOT-5 colour-infrared image (band combination: R = NIR, G = red, B = green).

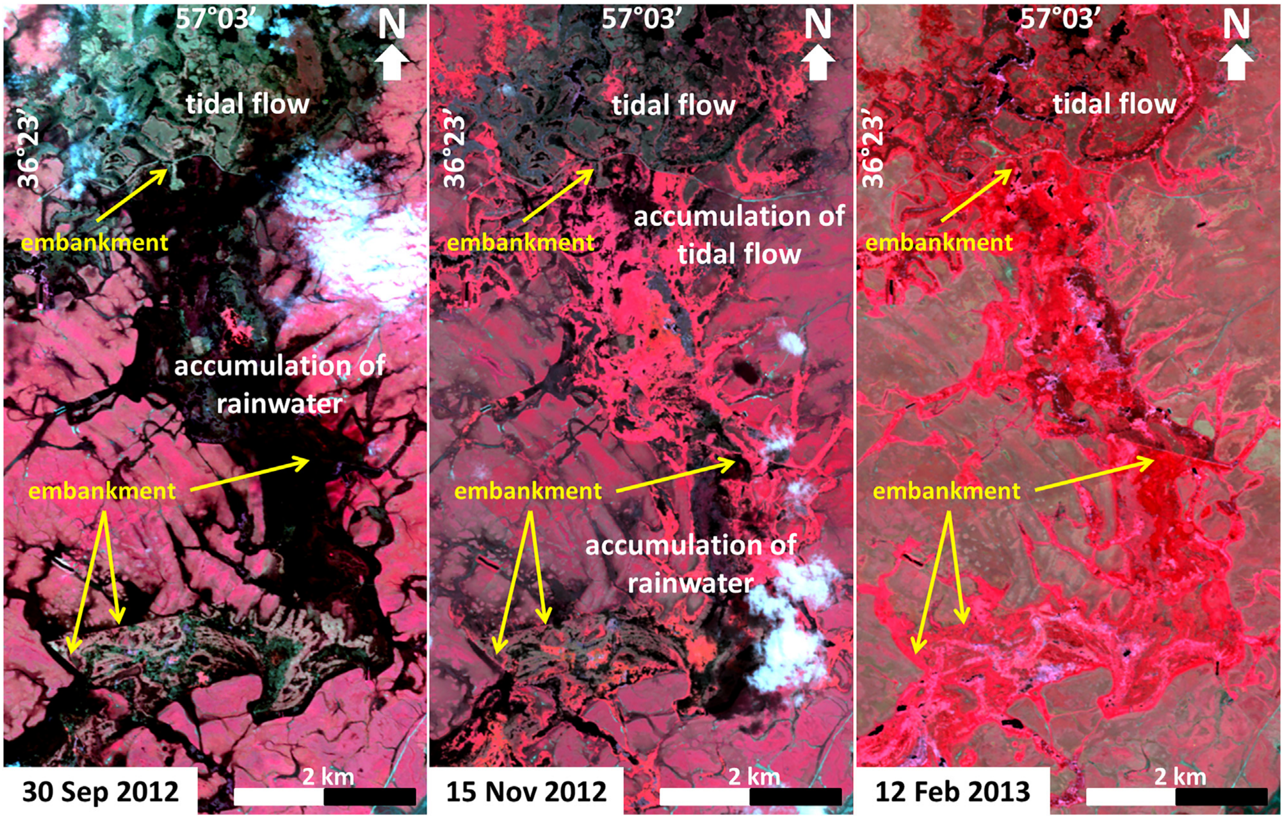

Fig. 4. Close-up of the lower basin and marsh areas in Fig. 3d, showing the embankments of the palaeo-Rincón de Ajó River under different hydrologic conditions (SPOT-5 colour-infrared images [band combination: R = NIR, G = red, B = green]).

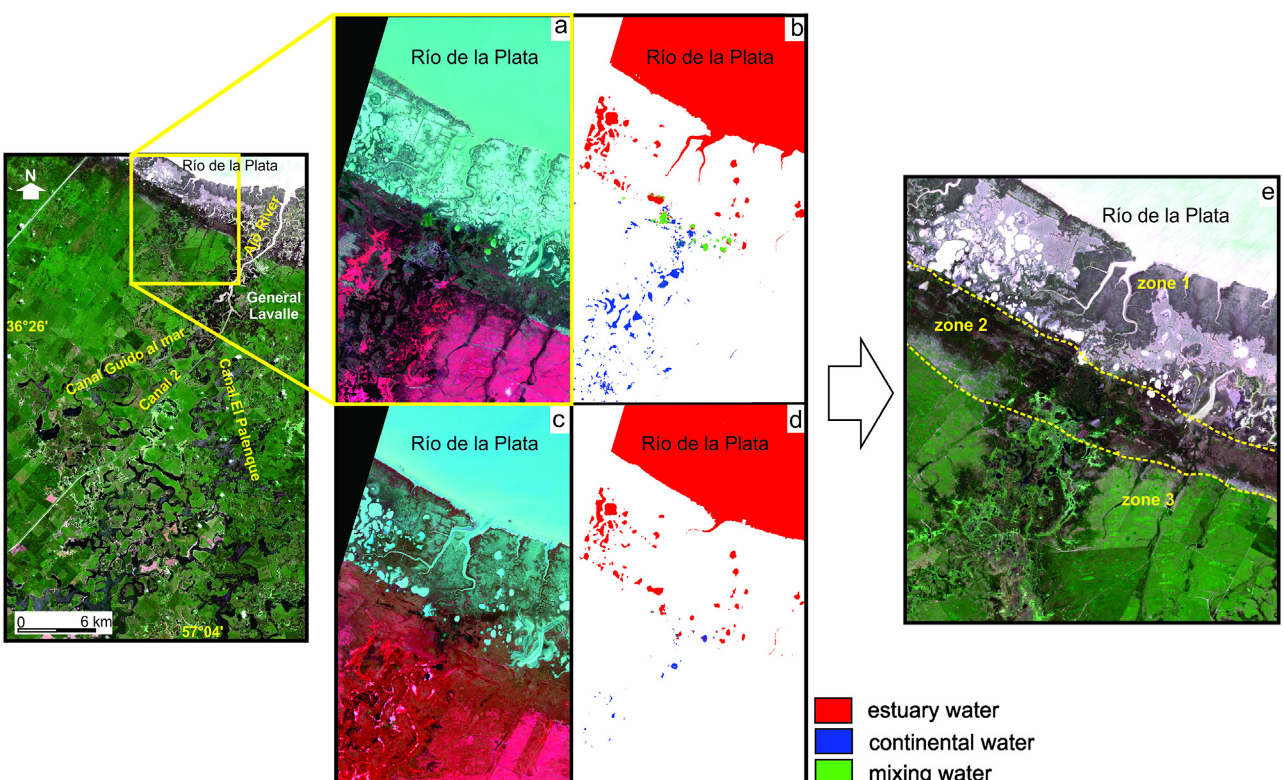

Fig. 5. Assessment of different type waters in the northern part of the palaeo-Rincón de Ajó River: SPOT-5 colour-infrared images (band combination: R = NIR, G = red, B = green), acquired on (a) 15 November 2012 and (c) 17 June 2013, in high and low tide conditions, respectively. The maximum likelihood classification is shown in (b) and (d): in red, turbid waters of the Río de la Plata; in blue, clear continental waters; in green, intermediate class with water mixing. The three zones differently affected by the tidal level are shown in (e); in the background, pseudo-true colour Sentinel-2 image (band combination: R = red, G = green, B = blue).

probably interconnected, with two drainage areas, separated by a narrow watershed, towards the bay. The ancient tidal channels of the central and eastern sectors tended to drain to the Ajó River, whereas the ancient tidal channels located in the western sector of the study area drained to the palaeo-Rincón de Ajó River, i.e. the present-day Cañada Rincón de Ajó (Fig. 3a and b).

The hydrologic landscape and natural drainage composed by these two watercourses that flow into the bay were modified by human-made channelizations and embankments built since 1890. The natural drainage area to the Ajó River was modified by the Canal El Palenque (Fig. 3c). However, as the course of this canal tends to follow the design of the ancient tidal channels, at a regional level it has introduced no relevant modifications in the hydrologic landscape of this sector of the coastal plain. This river has also been rectified in certain portions of the lower basin as a result of the dredging to allow ship access to the port.

The drainage area of the palaeo-Rincón de Ajó River was extensively modified, leading to the complete alteration of the hydrologic landscape. The analysis of the satellite images, supported by the cadastral records of the works (canals, embankments and routes), allowed the interpretation of the temporal evolution of the landscape depending on the anthropogenic modifications. The drainage area of the palaeo-Rincón de Ajó River was intercepted in the southern sector by the Canal 2 (Fig. 3c), built in 1902, which diverted the excesses of this sector of the coastal plain to the Ajó River. Consequently, the palaeo-Rincón

Fig. 6. Geographic charts of (a) 1866 and (b) 1888; cadastral maps of (c) 1890 and (d) 1896.

de Ajó River lost the contributions from a large portion of the upper basin, causing a decrease in surface water inflow. In turn, as the water table is shallow in the entire coastal plain area, the Canal 2—whose course in this sector is perpendicular to the groundwater flow—also intercepts the groundwater discharge that formerly contributed to the volume of water of the palaeo-Rincón de Ajó River. Subsequent to these works, the Canal Guido al Mar was devised, deviating to the Ajó River the surface and shallow groundwater flows of the south-central sector of the drainage area of the palaeo-Rincón de Ajó River (Fig. 3c).

Another modification introduced in the late 19th century was the embankment of the Ruta Provincial 11 (Provincial Route 11), which intercepts the drainage area of both rivers; however, the drainage area of the palaeo-Rincón de Ajó River was the one most deeply affected. This is due to the fact that the drain system of the embankments is limited; therefore, the route embankment also constitutes an obstacle for surface flow. The growth of livestock farming in the cattle farms of the lower basin of the palaeo-Rincón de Ajó River and the associated marsh area increased the number of embankments built for access roads to farms or to limit the tidal flow. All of these embankments (Figs. 3c and 4) have induced modifications over the past 50 years at a regional level. They conditioned the continental surface water flow and the one from the tidal flows, generating water accumulation areas on the surface that lack drainage. Embankments are still built at present, though at a smaller scale, by farm owners.

In the northern area, the palaeo-Rincón de Ajó River was connected to the Río de la Plata and, as it is currently visible in the case of the Ajó River, there was a superficial exchange between the discharge of continental water and the tidal flow. At present, there is no direct connection between the palaeo-Rincón de Ajó River and the Río de la Plata, but some evidence shows that the area is still affected by the tidal flow. Fig. 5 shows the results of the maximum likelihood classification applied to two SPOT-5 images, acquired under different tidal conditions. Considering only the aquatic targets, two major classes were identified: highly turbid waters, typical of the Río de la Plata, and clear continental waters, which occur inland. Turbid waters, classified as belonging to the same class as the Río de la Plata, are visible in the northern coastal strip, where intertidal mudflats are present. These water bodies are whitish and rich in suspended sediments, and they are directly connected to the Río de la Plata. On the other hand, continental waters are clear and dark, and they are probably the result of emerging aquifers or rainfall. During high tide conditions, continental water bodies expand, filling the now depressed relict river morphologies. Even though there is no connection with the Río de la Plata, the level of the emerging aquifers is modulated by the high tide. During high tide, a third additional class occurs in the

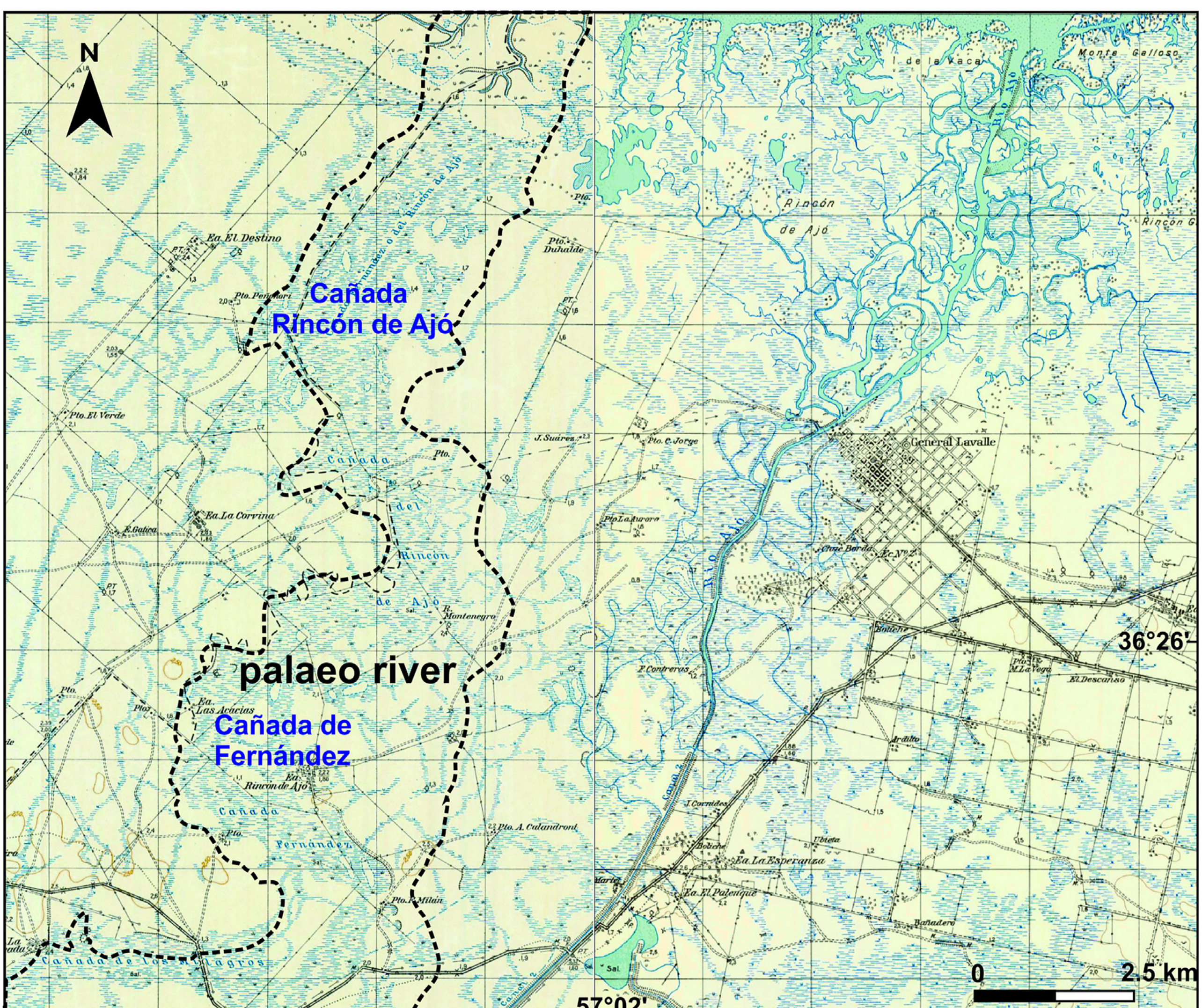

Fig. 7. Mosaic of topographic charts (1:50 000), surveyed between 1936 and 1941.

interface between mudflats and the continental area. This class is not present during low tide conditions and it is the result of the mixing of estuarine and continental waters. The comparison of the two classification maps shows some differences in the extent of water bodies due to tidal conditions. While the overall area of turbid waters increased by 10 % (989 600 m^2 and 849 000 m^2 during high and low tide, respectively), the extent of the continental waters increased greatly (873 500 m^2 and 92 800 m^2 during high and low tide, respectively). In conclusion, the northern part of the palaeo-Rincón de Ajó River is affected by the tidal flow, but we can distinguish three sub-zones (Fig. 5e): zone 1, where water bodies are superficially linked to the Río de la Plata, with sediment and water exchange; zone 3, where the tidal level modulates the level of the emerging aquifers; zone 2, where the water of the previous zones are mixed.

4.2. Past hydrologic landscape based on cartography and reconnaissance geology

In order to verify whether the palaeo-Rincón de Ajó River was a watercourse whose hydrologic landscape was modified by the anthropogenic modifications introduced in the recent past, historical maps of the area were gathered in search of evidence of its presence. Records of the morphology of the drainage in the coastal plain area can be found in historical maps since 1886. In the geographic chart of the Province of Buenos Aires surveyed in 1886, the drainage of the coastal plain is sketched schematically, showing four drainage courses (Fig. 6a). In the geographic chart of 1888, the drainage network is better represented: the courses of the Ajó River and of the palaeo-Rincón de Ajó River can be clearly observed (Fig. 6b).

The cadastral maps of 1890 show the hydrography of the area in a more defined manner, indicating in both maps three main drainage courses. The course located farther east would correspond to the Cañada Las Tijeras, which drains the interdune area to the west of the sand spit. The central sector of the coastal plain is drained by the Ajó River, into which two tributaries flow in the upper reach of the river. Finally, the sector located to the west, which in the cadastral maps coincides with the limit between the General Lavalle and Tordillo districts, is drained by a course called Cañada de Ajó, which may be the palaeo-Rincón de Ajó River. In the cartography, the three rivers have a well defined main course and similar length, close to 20 km. It should be noted that in these cadastral maps two modifications affecting the hydrologic landscape of the coastal plain can already be observed. One of them is the design of the route that connects General Conesa and General Lavalle (Fig. 6c and d) and the other is the canal built to widen the mouth of the Ajó River (Fig. 6d) in order to allow the access of ships in the heyday of the port.

In the older cartography, the drainage network involving the ancient tidal channels is not shown. It is not until the topographic charts (1:50 000 scale) surveyed between 1936 and 1938 (for the sector farther to the west) and between 1938 and 1941 (for the central sector) that the tidal channels can be observed in greater detail, although only in the case of those in the littoral area (Fig. 7). In these charts, important modifications of the hydrologic landscape are shown. In the topographic chart of the east sector, the course of the palaeo-Rincón de Ajó River does not have a definite course. Its name changes from Cañada de Fernández in the upper to middle basin section to Cañada Rincón de Ajó in the middle to lower basin section. From the source to the mouth at the bay, it is represented as a depressed area, with heights of less than 1.4 m above estuary water level, surface water flowing intermittently and no runoff channels. It still has the sinuous morphology of a tidal channel, even though its mouth at the bay is blocked by slightly higher land (with heights close to 1.6 m above estuary water level) and small independent tidal channels develop in the coastal area (Fig. 7). The main anthropogenic modifications documented in this topographic chart are the course of the Canal 2 and the design of the embankment of Ruta Provincial 11, which block the surface drainage in the area of the Cañada Fernández (middle basin). Minor embankments of access roads to farms can also be observed in the Cañada Rincón de Ajó (lower basin).

The topographic chart of the central sector of the coastal plain (Fig. 7) comprises the basin of the Ajó River, which has a definite course that is joined by numerous tidal channels. It should be noted that this course is rectified in several sections as a result of the dredging carried out to allow ships into the port. In the middle and upper basin, the superficial drainage is also channelized (Canal El Palenque) and in the middle basin it receives water from the drainage of the Canal 2. As in the case of the Cañada Rincón de Ajó,

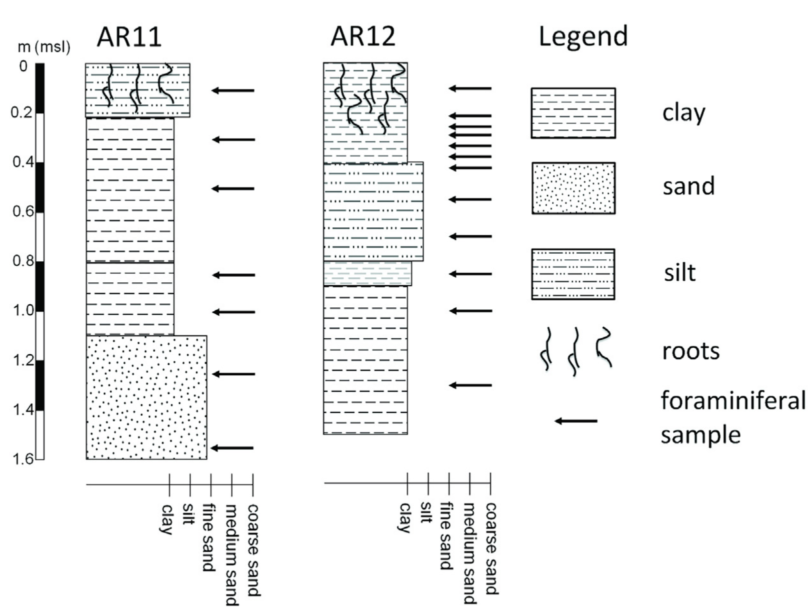

Fig. 8. Stratigraphic succession obtained from two cores, AR11 and AR12. Core position is shown in Fig. 3.

Table 1
Foraminiferal taxa in 9 sediment samples from the Ajó coastal plain: abundance percentage, total number of foraminifera, number of foraminifera per gram and number of taxa for each sample. In core AR12, 11 sediment samples from 0.21 to 1.3 m deep are devoid of foraminifera.

Core number	AR10	AR11	AR11	AR11	AR11	AR11	AR11	AR11	AR12
Depth (m)	0.01	0.1	0.3	0.5	0.85	1	1.25	1.55	0.1
Miliammina fusca (Brady, 1870)	4.2	–	–	–	–	–	–	–	–
Trochammina inflata (Montagu, 1808)	91.7	66.7	–	–	–	–	–	–	*
Trochammina macrescens (Brady, 1870)	–	33.3	–	–	–	–	–	–	*
Spirillina vivipara Ehrenberg, 1843	–	–	–	–	–	–	0.7	–	–
Spiroloculina lucida Cushman & Todd, 1944	–	–	–	–	–	–	0.7	0.5	–
Quinqueloculina seminulum (Linné, 1758)	4.2	–	8.2	–	–	–	55.0	46.6	–
Miliolinella subrotunda (Montagu, 1803)	–	–	2.7	–	–	–	14.6	13.6	–
Triloculina trigonula (Lamarck, 1804)	–	–	–	–	–	–	–	0.5	–
Oolina laevigata d'Orbigny, 1839	–	–	–	–	–	–	–	0.5	–
Oolina exagona (Williamson, 1848)	–	–	–	–	–	–	–	0.5	–
Fissurina lucida (Williamson, 1848)	–	–	–	–	–	–	0.7	–	–
Brizalina spathulata (Williamson, 1858)	–	–	–	–	3.0	–	–	1.0	–
Valvulineria perlucida (Heron-Allen & Earland, 1913)	–	–	2.7	–	–	–	–	–	–
Discorbis mirus (Cushman, 1922)	–	–	8.2	*	–	–	6.6	4.9	–
Rosalina cf. candeiana d'Orbigny, 1839	–	–	8.2	*	–	–	8.6	15.5	–
Discorbinella bertheloti (d'Orbigny, 1839)	–	–	1.4	–	–	–	–	1.0	–
Haynesina paucilocula (Cushman, 1944)	–	–	–	–	–	–	0.7	1.5	–
Nonion sp.	–	–	1.4	–	–	–	–	–	–
Buccella peruviana (d'Orbigny, 1839)	–	–	9.6	*	3.0	–	–	–	–
Buccella pustulosa Albani and Serandrei Barbero, 1982	–	–	–	–	–	–	0.7	–	–
Ammonia beccarii (Linnè, 1758)	–	–	24.7	*	30.3	11.4	4.6	4.9	–
Cribrononion granosum (d'Orbigny, 1846)	–	–	17.8	**	45.5	81.8	6.6	9.2	–
Cribrononion lagunensis Albani and Serandrei Barbero, 1982	–	–	11.0	–	6.1	–	0.7	–	–
Cribrononion translucens (Natland, 1938)	–	–	4.1	–	12.1	6.8	–	–	–
Total	144	80	1095	41	116	176	9966	7210	*
Forams per gr	5,6	2	26	1	2	4	185	153	–
Number of taxa	3	2	12	5	6	3	12	13	2

the Ruta Provincial 11 crosses the Ajó River perpendicularly to the surface runoff (Fig. 7).

4.3. Sediment samples

Sediment samples were collected at depths between 0.1 and 1.6 m from areas that, before the anthropogenic modifications, belonged to the catchment area of the palaeo-Rincón de Ajó River. The lithology and organogenic content of 20 sediment samples provided information about the depositional environment (Fig. 8, Table 1). Although taphonomic processes may modify Holocene foraminiferal assemblages, in the deepest samples of core AR11 the abundance of *Quinqueloculina seminulum,* a fragile species not often preserved in fossil assemblages in this area (Laprida et al., 2011), indicates that the foraminiferal assemblages analyzed are only slightly affected by these processes. Foraminiferal analyses, therefore, provide a reliable palaeoenvironmental reconstruction.

In the area between the Canal 2 and Canal Guido al Mar (AR11, Figs. 3 and 8), sediments from a depth of 1.6 to 1.1 m consist of fine sand. They contain a foraminiferal assemblage (Table 1) dominated by the two miliolids *Miliolinella subrotunda* (14–15 %) and *Quinqueloculina seminulum* (55–47 %). From 1.1 to 0.2 m deep, the clayey sediments contain an assemblage with few foraminifera species, dominated by *Cribrononion granosum* (18–82 %) and *Ammonia beccarii* (10–30 %). At the top, sediments are constituted by clayey silt with fine sand. They contain abundant plant remains, roots and the foraminifera *Trochammina inflata* and *Trochammina macrescens.*

North of the embankment of the Ruta Provincial 11 (AR12, Figs. 3 and 8), sediments were sampled up to a depth of 1.5 m. They are composed of clay and silty clay between 0.8 and 0.4 m deep and contain abundant plant remains. A dense sampling was carried out in the highest part of core AR12 to analyze any environmental changes in recent times. Analyses have not revealed the presence of foraminifera (Table 1). In the upper part, between 0.2 and 0 m deep, the silty clay with abundant roots and plant remains contains only sporadic specimens of *Trochammina.*

A sample of surficial sediments has been analyzed. It comes from the north-eastern sector of the coastal plain, currently drained by the Ajó River (AR10, Fig. 3). In this sample, the species *T. inflata* comprises almost the totality of the assemblage (Table 1).

5. Discussion

In the Ajó coastal plain, an area characterized by muddy and waterlogged sectors, the analysis of satellite images revealed the presence of a meandering landform on which the modern cartography does not show any information. Integrating remote sensing data with historical maps, it was possible to ascribe this relict landform to the ancient watercourse of the Rincón de Ajó River, now silted up.

Considering the Ajó wetland at a regional scale, the presence of few anthropogenic structures, such as drainage canals and embankments, would seem to have induced negligible effects on such a large natural environment. However, a careful analysis of the hydraulic connectivity and water exchange between the surface water and the underlying aquifers pointed out that the engineering works, even though they involve relatively local portions of the wetland, significantly modified the hydrologic landscape at a regional scale. The conceptual model of the evolution of the hydrologic landscape in the drainage area of the palaeo-Rincón de Ajó River—based on the integrated interpretation of satellite images, historical maps, geomorphological surveys and sediment analysis—is shown in Fig. 9.

Under natural drainage conditions, the water surpluses of the coastland were intercepted and discharged into the bay by the palaeo-Rincón de Ajó River and the Ajó River, while the estuary water could encroach the various channel mouths during high tides, forming the freshwater-saltwater mixing zone in the littoral sector, typical of transitional coastal environments.

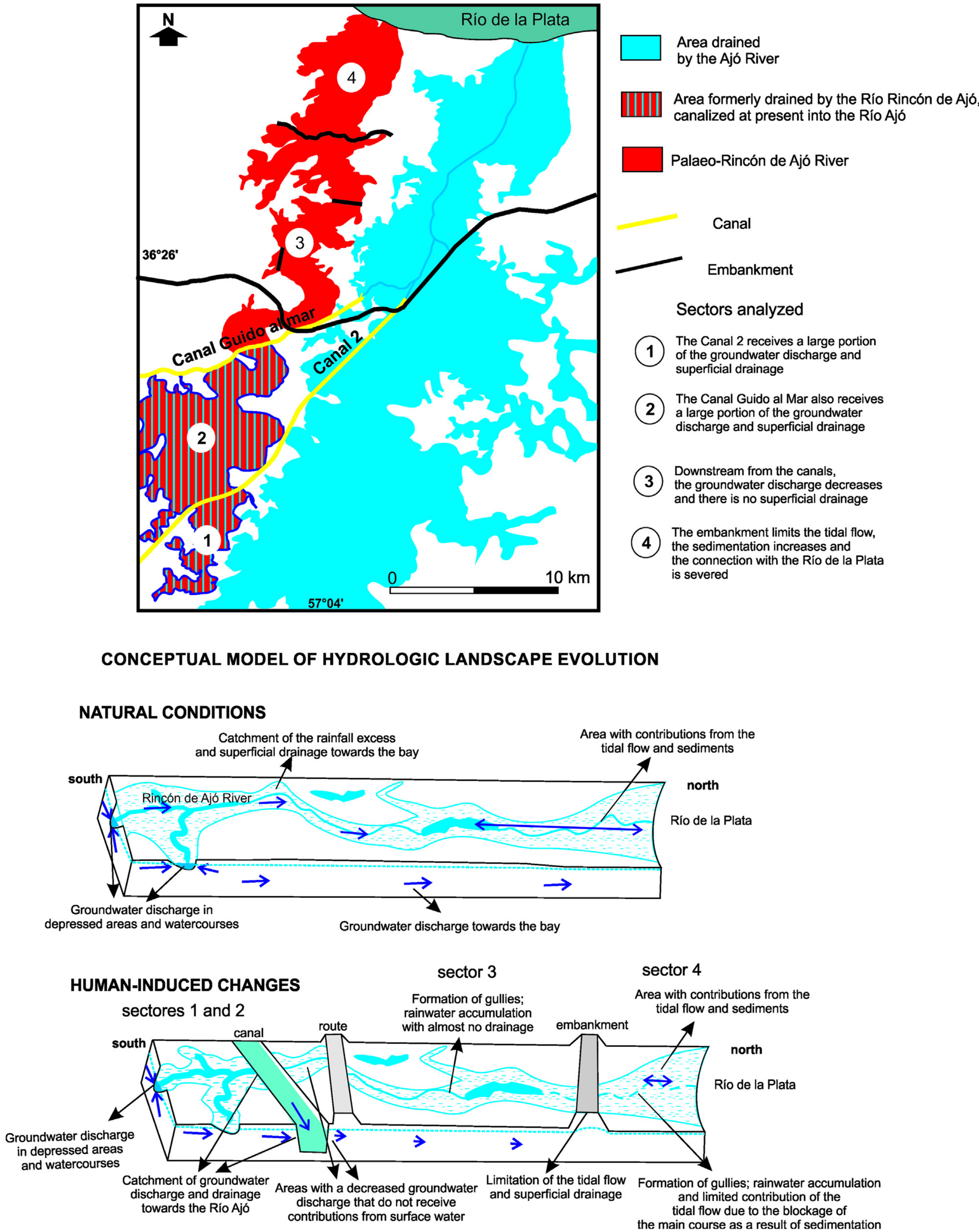

Fig. 9. Conceptual model of hydrologic landscape evolution of the palaeo-Rincón de Ajó River.

The building of the Canal 2 and Canal Guido al Mar in the northern and central catchment areas of the palaeo-Rincón de Ajó River (i.e. sectors 1 and 2 in Fig. 9) diverted the natural drainage of the surface water and part of the regional groundwater flow of the Ajó coastland towards the Ajó River. The Canal 2 and Canal Guido al Mar drain an area of 16.0 and 56.0 km^2, respectively, representing 45.5 % of the original basin of the palaeo-river. As a result, the presence of surface water downstream from the Canal 2 and Canal Guido al Mar, which accumulates in the lowlands of the former tidal channels within the natural drainage area of the palaeo-

Rincón de Ajó River, is mainly the result of rainfall and water table seepage during wet periods.

The construction of the Ruta Provincial 11 embankment and the tidal embankment blocked the natural surface runoff to the bay in the north, as well as the natural ingression of estuarine water through the former tidal channels of the palaeo-Rincón de Ajó River in the south. The presence of such embankments affects approximately 86.5 km^2 of the palaeo-river basin, i.e. about 54.5 % of the palaeo-Rincón de Ajó River basin. As a result of the combination of sediment yield accumulation from the estuary in sector 4 and the starvation of the water flow due to the lack of continental water drainage in the other sectors, most of the palaeo-Rincón de Ajó River channel system has been progressively filled. Consequently, the temporal presence of waterlogged sectors along the path of the ancient watercourse is now related to rainfall and seepage from the water-table rise during wet periods and extraordinary high tide events, which may exceed the embankment and flood sector 3 (Fig. 4 b, c and Fig. 9). In turn, the Ajó River, in spite of the various human interventions (i.e. the digging of drainage canals, the construction of tidal and road embankments, the dredging and rectification of the course to allow the entrance of boats), shows a typical intertidal morphology.

Micropalaeontological analysis also confirms this reconstruction. Surficial sediments from the Ajó River marsh located in the north-eastern sector of the coastal plain (AR10, Fig. 3) contain *T. inflata*, an indicator species in salt marshes occurring in this area where fresh- and saltwater are mixed. In AR11, the deepest sediments are dominated by the miliolids *M. subrotunda* and *Q. seminulum*, common species in the subtidal facies of the modern beaches of the Samborombón Bay (Laprida et al., 2011). In the middle part of the core, the foraminiferal assemblage is poor and controlled by stress-tolerant species: in particular, *C. granosum* is able to withstand wide fluctuations in salinity (Donnici and Serandrei Barbero, 2005). These sediments are typical of a back-barrier facies. Surficial sediments in AR11 are characterized by a salt marsh foraminiferal fauna. According to these analyses, the southern part of the coastal plain has evolved from a subtidal environment close to shore to a back-barrier environment and, lastly, to a salt marsh, reflecting the Holocene migration of the coastline. At present, this area is drained by the Canal 2 and it appears to be influenced by the tide through the active channels. In AR12, the analyses have not revealed the presence of foraminifera. The depositional environment of the sedimentary record is attributable to a freshwater swamp for the whole thickness. The area between the two embankments does not seem to be influenced by the tide and it appears to have also had a freshwater nature in the past. The Ajó coastal plain is an example of an intertidal wetland in which the channelizations and embankments have modified the hydrologic landscape at a regional level.

The anthropogenic modification of coastal areas has a long history and it has been studied extensively in Europe and North America (Brown et al., 2017). For example, the Ebro delta (Spain) did not exist prior to the Roman period, and so it is the result of a late Holocene, anthropogenically accelerated sediment supply (Xing et al., 2014). The landscape of the Venice Lagoon (Italy) has changed from its formation up to the present day, due to natural factors as well as human activities, such as the artificial diversion of rivers (Tosi et al., 2009 and references therein) and the modification of the lagoon inlets (Amos et al., 2010). In particular, the hydrology has changed, since the number of channels has decreased over the past centuries (Madricardo and Donnici, 2014) and the extension of the salt marshes has experienced a drastic reduction during the 20th century (Serandrei-Barbero and Donnici, 2014, and references therein). In the Dee estuary (UK), navigation works at the head of the estuary caused rapid salt-marsh accretion along the English shore, replacing the low-water tidal channel and beach (Marker, 1967; Clarke and Tully, 2014). In the United States, it has also been documented that most coastal wetlands have been subject to anthropogenic impact (e.g. Silliman et al., 2008). Louisiana coastal wetlands have been disappearing at an alarming rate due to natural and anthropogenic processes, including sea level rise, land subsidence and infrastructure development (Oliver-Cabrera and Wdowinski, 2016). However, the contributions that report the increase of coastal wetland areas are few. Worldwide, the extent of coastal plains and marshes has decreased considerably, mainly due to channelizations, embankments, underground cut-off walls to prevent saltwater intrusion, and urban development (e.g. Beauchard et al., 2011; Gedan et al., 2009). In particular, sea walls, dykes, embankments, and channelizations were widely used in the last century for coastal wetland reclamation and flood risk mitigation. The lack of any assessment of the impact of human interventions on the hydrology of wetlands is mainly due to a lack of awareness of the importance of the ecosystem services provided by wetlands (Gedan et al., 2009).

In the Ajó coastal plain, a watercourse documented in maps from 120 years ago became a relict fluvial landform (palaeo-river) due to anthropogenic changes. Even though it could be considered that its deactivation may be due to natural processes of the temporal evolution of the landscape, the analysis of satellite images, cartography and historical documentation, together with field surveys, have shown that anthropogenic modifications are the main reason.

At present, the palaeo-Rincón de Ajó River is still a wetland area, but its hydrological behaviour does not depend any longer on the superficial drainage or the periodical exchange with the tidal flows. Depending on the alteration of the hydrologic landscape, the different sectors of the palaeo-river's basin function as depressed areas, separated by embankments in which the rainwater accumulates and which receive the local discharge of the groundwater flow. A portion of these areas (mainly the upper basin) drain to the Ajó River, which, together with the embankments, leads to a disconnection between the water flow in the different sectors of the basin. Even though occasionally the coastal sector may receive tidal contributions when the high tide exceeds the embankments, these areas remain waterlogged and are far from representing the typical tidal exchange of marshes. As can be observed in the field surveys, these hydrologic modifications have led to changes in the soil and vegetation. In the main course and the adjacent plain, these changes have caused a decrease in sediment transport capacity and the clogging of the drainage basin, mainly due to the accumulation of organic matter (Thom, 1992), where abundant hydrophytic vegetation grows. This vegetation changes from intertidal saline vegetation to the freshwater-dependent type, a characteristic that can be observed in other marshes affected by embankments (Roman et al., 1984; Portnoy, 1999).

6. Conclusions

Evidence suggesting the presence of a meandering channel system not represented in modern maps was identified by satellite imaging in the lower part of the Samborombón Bay coastland. The analysis of historical maps and in situ surveys highlighted that significant hydrologic landscape changes have occurred over the last 120 years. In order to understand whether the disappearance of the ancient river channel is due to natural processes or human-induced causes, multispectral data acquired under different soil moisture, surface water and tidal conditions have been analyzed and interpreted, together with current and historical maps.

This ancient channel may have constituted the lower part of the palaeo-Rincón de Ajó River, which disappeared because it was cut off from its flow and because of its silting up after the dredging of new drainage canals and the construction of a number of embankments for roads and to prevent the flooding of the wetlands from the Río de la Plata estuary. In fact, the human-made interventions completely changed the natural relationship between the groundwater and superficial water in the Ajó coastal wetlands, leading to significant hydrologic landscape modifications in the last century. The regional-scale modification of the hydrologic landscape registered in the wetland of the Ajó coastal plain is caused by several local modifications. This shows why it is essential to undertake a hydrological and environmental impact assessment at a regional level before carrying out any engineering works in wetlands. The case of the Ajó coastal plain should be an example to foster joint research by ecologists and engineers, and to motivate governments and industry to support the wider implementation of ecosystem-based flood defense.

To conclude, the conceptual model of hydrologic landscape evolution implemented in this study would be used to further evaluate the synergy that every new engineering works may have on the pre-existing works.

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