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Morphodynamics, sedimentary and anthropogenic influences in the San Vicente de la Barquera estuary (North coast of Spain)

G. FLOR-BLANCO[1] **G. FLOR**[1] **L. PANDO**[2] **J. ABANADES**[3]

[1]**Dpto. Geología, Facultad de Geología, Universidad de Oviedo. GeoQuo Research Group (Geomorphology and Quaternary)**
33005 Oviedo, Asturias. Flor-Blanco E-mail: gfb@geol.uniovi.es Flor E-mail: gflor@geol.uniovi.es

[2]**Dpto. Geología, Facultad de Geología, Universidad de Oviedo. Geology Applied to Engineering Research Group**
33005 Oviedo, Asturias. Pando E-mail: lpando@geol.uniovi.es

[3]**Plymouth University, School of Marine Science and Engineering**
Marine Building, Drake Circus, Plymouth PL4 8AA, UK

ABSTRACT

The estuary of San Vicente de la Barquera (Cantabria, Spain) occupies two fluvial valleys that have incised into soft sedimentary rocks (Lower Mesozoic) and are controlled by inactive faults. These two estuary subsystems, the Escudo (main valley) and Gandarilla, share outer estuarine zones, *i.e.*, a sandy bay and an estuary-mouth complex. The complexity of the system lies in the presence of a confining barrier formed by an aeolian dune/beach system that is currently enclosed by a jetty, which has allowed the dune progradation over the past 50 years. Furthermore, connected to the inner inlet in the sand bay there is a flood-tidal delta, the most important morpho-sedimentary and dynamic unit. This unit exhibits a heart shape caused by the wide range of flows in this estuarine zone and channelizes the flows and sediments into the estuary, primarily during rising and high tides. In particular, the counter-clockwise surficial rotation due to the Coriolis effect is essential to the development of sand shoals, spill-over lobes, sand waves and megaripples. The presence of estuarine beaches into the bay is common in many Cantabrian estuaries, even culminating in small dune fields, in this case due to anthropogenic influences. This paper explains the impact on the estuary of human occupation and port management, focussing on the dynamic and sedimentary distribution of a bar-barrier estuary and the changes produced in its distal part by the construction of the two jetties in the mouth.

KEYWORDS **Estuary. Progradation. Flood-tidal delta. Coriolis. Anthropogenic influences.**

INTRODUCTION

Despite the large number of studies focussed on sediment dynamics, surficial facies distribution and vertical evolution by siltation filling of mesotidal estuaries (Hayes, 1980; Borrego *et al*., 1993; Dyer, 1995; Morales *et al*., 2014), there are just a few examples illustrating the role played by human activities on the depositional system.

Shoreline changes are often caused by man-made structures, mainly in estuary mouths, for instance, the construction of jetties (Flor-Blanco *et al*., 2015) or dams changes drastically the estuarine circulation and the siltation patterns (Traini *et al*., 2013). The present paper deals with the evolution of the estuary in San Vicente de la Barquera (Spain), where two jetties have channelised the inlet in the northern part of the estuary. This corroborates that anthropogenic changes have intense and rapid influences on the system (Flor and Flor-Blanco, 2005; McFadden *et al.*, 2006; Dugan *et al.*, 2011) and lead to the acceleration of geomorphical processes, which consequently have not always been caused primarily by climatic factors (Bruschi *et al.*, 2013).

There are numerous examples around the world that exemplify this (*e.g.* Wooldridge *et al.*, 1999; Parchure and Teeter, 2002; Kelley and Brothers, 2009). For example, in the Iberian Peninsula the Mondego and Douro estuaries in Portugal studied by Bettencourt *et al.* (2009), Foz (NW Spain) by Díez *et al.* (2006), the Huelva coast (SW Spain) studied by Rodríguez-Ramírez *et al.* (2008), and near the study area in Avilés, Asturias, by Flor *et al.* (2006), López-Peláez and Flor (2008) and Flor-Blanco *et al.* (2013).

On this ground, the present paper is focussed on the estuary of San Vicente de la Barquera (Cantabria, Spain). This estuary is constricted by an artificial narrow inlet, sand bodies and bedforms formed by ebb and flood currents, such as a large flood-tidal delta and spillover lobes. According to Hume *et al.* (2007) it can be classified as Category E where the tidal volume is higher than the volume delivered by the river flow during a tidal cycle.

The aim of this study is to characterise the morphology and dynamic patterns in a beach-dune system and its associated bay from the confinement of the bar-barrier by two jetties. For this purpose, a dynamic model based on the control of the current velocity, direction and water salinity is applied, emphasising the presence of a large-scale levorotatory circulation attributable to the Coriolis effect. The application of this model to the Cantabrian coast, a complex natural coastal system with many small estuaries, will allow a detailed investigation of the morphodynamical effects and a future extrapolation of the results to larger estuaries worldwide.

GEOLOGICAL AND GEOMORPHOLOGICAL SETTINGS

The San Vicente estuary is located in western Cantabria, northern Spain (Fig. 1), and it is formed by two very shallow estuary subsystems and elongated perpendicular to the coastline, which flow into two relatively independent estuarine valleys, constricted by a sand barrier at the mouth. The principal axis is oriented N–S and is connected to the Escudo River. This river empties into the Rubín embayment, which occupies an area of 3.7km^2 (Table 1) and is responsible for the development of most of the morphosedimentary units. The Pombo, the secondary embayment, is aligned NE–SW, and receives drainage from the Gandarilla River (9.55km^2), being responsible for an estuarine surface of 1.2km^2 (Table 1). This dual estuary geometry is also seen elsewhere. For example, in the Eo stuary (Flor, 1995), Avilés estuary (López Peláez and Flor, 2008; Flor-Blanco *et al.*, 2013), the Bay of Santander (Dantín Cereceda, 1917) in the north of Spain; in the Río Tinto and Odiel estuaries (Pendón *et al.*,1998) and the Piedras estuary (Morales *et al.*, 2006) in the south-west of Spain; and in the Mondego estuary (Cunha and Dinis, 2002) in Portugal.

Based on the geomorphological maps from the mouth to the limit of tidal influence during spring tides, the two river arms share a common area, the mouth and the sandy bay. Both subsystems acquired a triangular geometry elongated in a plan view. From the outer river mouth (marine influence) to the tail (fluvial influence). The lithologies grade from sands (the study area) to silt in response to a decrease in energy (Dalrymple *et al.*, 1992). The estuarine geometry is controlled by the diverse composition of the geological substrate which consist of carbonates, siliciclastics and evaporites (Keuper reddish siltstone and gypsum) of lower Mesozoic age affected by a complex network of faults with participation by halokinetic processes (Portero García *et al.*, 1976). These features are also observed in the large systems of other Cantabrian estuaries (*e.g.* Avilés, Villaviciosa, Santander, Asón and Guernica).

In the present paper, the terrigenous materials need to be characterised in relation to the siliciclastic contributions from the neighbouring estuaries of Tina Mayor and Tina Menor (Flor-Blanco and Flor, 2008), located only a few kilometres to the west of San Vicente de la Barquera estuary. The persistent coastal eastward current in the Bay of Biscay, is responsible for the net transport of fluvial sandy sediment from west to east. In contrast, the coastal rivers of San Vicente de la Barquera estuary (Fig. 1), Escudo (Rubín) and Gandarilla (Pombo) contribute comparatively with low volumes of sediment. Other Atlantic estuaries developed in rocky coasts reveal a sedimentary infilling of incised valleys corresponding to the Holocene transgression. Several estuary typologies can be ranged from ria-type valley (García-García *et al.*, 2005) to tide –and wave– dominated estuaries, which are more abundant around the world (Tessier, 2012) with some of them presenting very low sedimentary infilling (Ménier *et al.*, 2010; Tessier *et al.*, 2012).

Conceptual stratigraphic models for tide– and wave–dominated estuaries with sedimentary infilling were proposed by Dalrymple *et al.* (1992). These models are similar to the model applied in this study because they represent a single transgressive–regressive cycle (Tessier, 2012), as well as the sedimentary sandwich (Weber *et al.*, 2004).

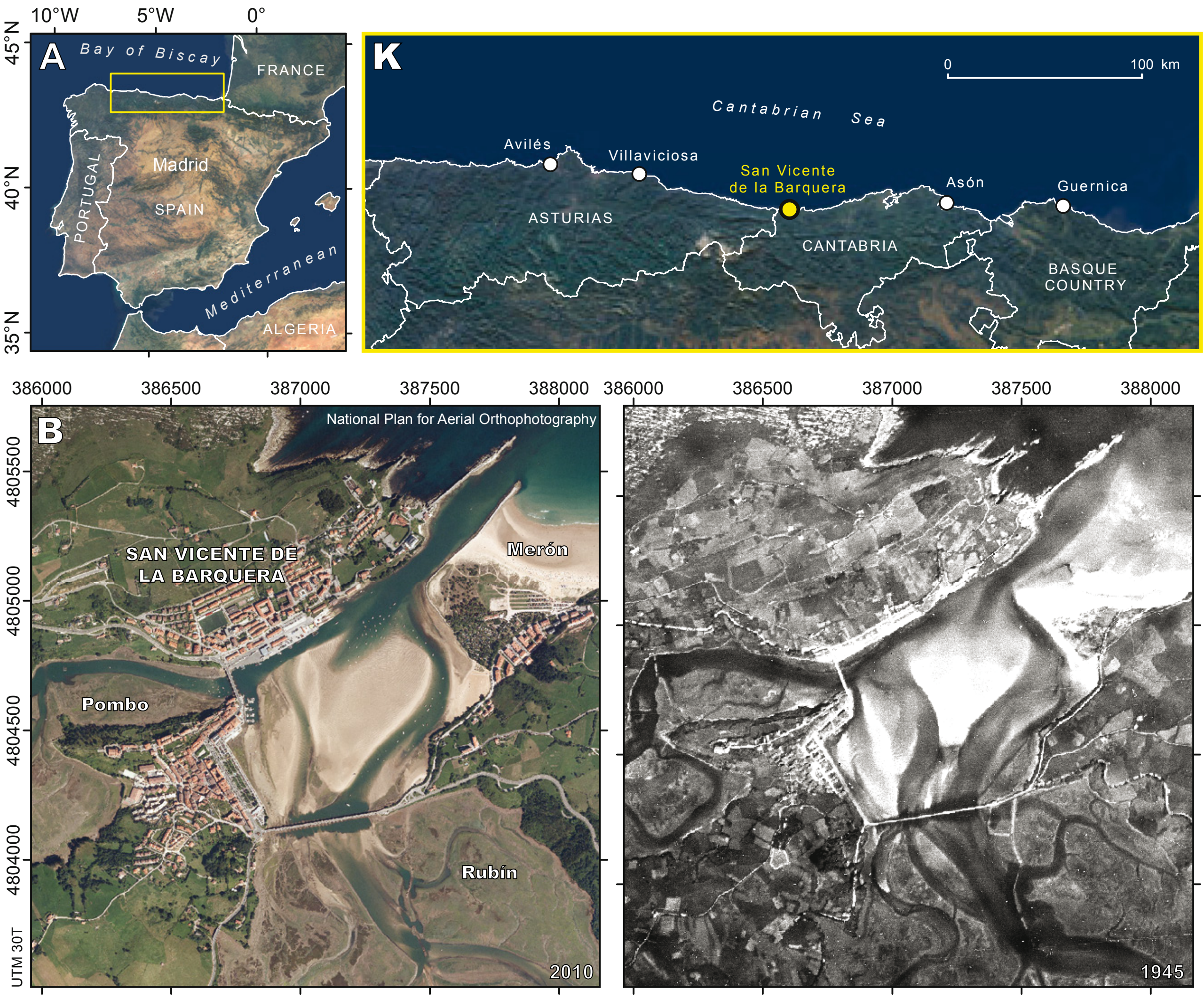

FIGURE 1. A) Situation of San Vicente estuary outer sector in Northern Spain (W Cantabria). B) Aerial photograph in 1945 (IGN-CECAF) and ortophotograph in 2010 (PNOA-IGN).

The coast analysed in the present paper is considered a high-energy environment with strong and persistent winds from various directions when the Azores High System affects the Iberian Peninsula. The wave periods most often range from 5 to 22s, and frequently between 8 and 12s (Castaing, 1981). While swell waves come most generally from the NE (González *et al*., 2004), the most predominant direction for sea waves is NW to NE. Moreover, the most frequent significant wave heights vary between 1.0 and 1.5m, and the peak period varies between 6 and 14s (M.O.P.T, 1992).

The tide (semidiurnal and mesotidal) is the most important dynamic factor with ranges between 1.0m and 4.75m and an average of 2.84m (mesotidal estuary). In this case, however, the estuary is hypersynchronous, based on the criteria of Le Floch (1961), who combines the balance of the estuary convergence and the frictional effect.The tidal range is slightly higher in the tidal flat area than in the mouth during the high tide. This is due to the formation of a resonance produced standing wave in which the node is located at the entrance and the antinode is located at the middle portion of the muddy flats, as Ribadesella estuary (Flor and Camblor, 1990), based on the concepts developed by Eagleson and Dean (1966).

MATERIAL AND METHODS

The data presented in this study include geomorphological mapping and monitoring for several years and interpretation of historical photographs: 1953 (1:15,000), 1975 (1:18,000), 1997 (1:18,000), 2001 (1:5,000), 2007 (1:5,000) and 2010 (1:5,000).

Topographic maps (1:5,000) of each region, with the Digital Terrain Model (DTM) (obtained from the Servicio Cartográfico de Cantabria) and the estuary distribution in

TABLE 1. Area and areal percentages calculated for the main geomorphological zones and their morphosedimentary and dynamic units

	Area (m^2)	(%)
MOUTH COMPLEX	372,227.19	6.23
Inlet		
Main channel	61,682.11	1.03
Ebb bar	27,050.85	0.45
Confinning barrier		
Exposed beach	114,324.22	1.91
Active dune field	30,876.99	0.52
Inner reclaimed dune field	138,293.02	2.32
BAY	617,666.99	10.35
Main channel	118,102.65	1.98
Secondary channel	93.137.94	1.56
Flood-tidal delta	226.012.59	3.79
Sand flats	154,642.05	2.59
Estuarine beaches	23,775.68	0.40
Estuarine dunes	1,995.98	0.03
TIDAL FLATS RUBÍN SUBSYSTEM	3,560,453.34	59.64
Main channel	366,631.75	6.14
Channel bars	34,311.31	0.57
Spill-over lobes	11,005.36	0.18
Mud flats	2,328,427.52	39.00
Reclaimed mud flats	820,077.40	13.74
TIDAL FLATS POMBO SUBSYSTEM	1,278,938.02	21.42
Main channel	127,443.56	2.13
Mud flats	670,060.26	11.22
Reclaimed mud flats	481,434.20	8.06
UPPER CHANNEL RUBÍN SUBSYSTEM	133,855.16	2.24
Main channel	32,600.11	0.55
Channel bars	58,319.36	0.98
Reclaimed fluvlal-tidal flats	42.935.69	0.72
UPPER CHANNEL POMBO SUBSYSTEM	7,172.41	0.12
Main channel	1,077.20	0.02
Reclaimed fluvial-tidal flats	6,095.21	0.10
TOTAL	5,970,313.01	100

1860 (Riudavets, 1871) permitted precise interpretations of, including settings in the position of the jetties in detail, and the inner estuary evolution.

Based on detailed historical aerial photographs and maps from the last century, horizontal accretions and recessions were quantified, and the surfaces of the morphodynamic units were identified. To analyse the evolution of the Merón dune field, three profiles were drawn (east, central and west) (see Fig. 2). Each profile was drawn on a base of georeferenced aerial photographs or orthophotos and compared with the previous profile using ArcGIS 9.3. In this manner, the rates of dune front accretion or erosion were calculated. To update the data, in 2014, in situ measurements were performed using a Leica Disto D5 laser distance meter and a GPS.

For tidal height measurements, three stations were established along the entire estuarine axis. These stations were located at the estuary mouth, intermediate portion (Fig 2) and the other in the tail. The measurements were made during spring tide conditions and near-average river flows, as these conditions are more representative of the dynamic activity. The recordings were conducted over a full tidal cycle with data taken during high tide at intervals of 10 minutes, except at the upper channel stations, where, due to the delay and lower variations in the tidal range, the recording intervals were slightly longer. The salinity was measured using YSI Model 556 multiparameter sonde and current speeds and directions with a General Oceanic, Inc. Model 2031H and a Global Water 800-876-1172 Model FP101, all from a motor boat. For this purpose, a series of estuarine cross sections from the mouth of the estuary to near the tail, the measurement stations were situated (Fig. 2). At these measuring points, the salinity, current speed and direction were measured from the surface to the bottom at intervals of 0.50m (minimum of three in all cases and up to five at high tide). The recordings were concentrated at representative times during the tidal cycle: high tide, midway during a falling tide, low tide and midway during a rising tide. The runoff data from the coastal rivers that drain the estuary were obtained from a study by GHESA (2005), and salt water volumes were calculated for spring and neap tides. The mixing waters (Table 2) show the extreme and average volumes of fresh and salt waters into the estuary.

RESULTS

Geomorphological zonation

The criteria for dividing the estuarine system into longitudinal zones (perpendicular to the coastline) were established based on: i) the energy level and dynamics of specific agents: waves, tides and fluvial discharges (Dalrymple *et al*., 1992); ii) the predominance of a certain sedimentary fraction; iii) the morphosedimentary-dynamic units; and iv) the inorganic and organic sedimentary bedforms (Table 3). There are four morphologic zones, which are characterised by a series of morphosedimentary and dynamic units (Flor, 1995). These zones are the mouth complex, bay, tidal flats and upper channel. This study focuses primarily on the evolution of the first two zones and the northern part of the third (Fig. 3).

Mouth Complex

The mouth complex is the most modified zone, as the mouth inlet has been channelised along both margins, thus extending the inlet out to sea. For this reason, a new dune field has been formed due to progradation. The old dune field complex was colonised by arboreal vegetation and has been partially destroyed by the modifications of a campsite; the complex occupies an area of 372,227.19m^2 (Table 1).

At certain times, there is an outer sandy mouth bar whose morphology is poorly defined but tends to take an arcuate shape with the convexity facing offshore. This bar is connected to the outermost portion of the channel mouth (Fig. 3) and a problem for the management of the port since requires periodic dredging. Moreover, the tidal inlet, generally experience heavy sedimentation induced by wave action (Van Rijn, 2005), which prompted the construction of the jetties.

The tidal inlet corresponds to the distal segment of the main channel and has a length of 670m and a variable width (maximum of 160m); this inlet is developed in the portion of greater estuarine confinement. The inlet also contains semi-permanent spillover lobes generated by the ebb and located between the inner right portion and the middle of the inlet (Fig. 3).

The sand mouth barrier is formed by the Merón Beach/dune system, specifically its western end, although it is highly modified by anthropogenic structures. The jetties were built in 1944 and encouraged the growth of the dune field, leading to seaward migration of the beach of 275m (west part) and 140m (east–central part) until 2010 (Fig. 4).

The old dune field (Fig. 2) is slightly more than 200m wide, and the active dunes are no more than 20m wide. These active dunes consist of a foredune zone in contact with the backshore zone and certain tongue-like dunes or lee-projection dunes. The outer edge of the dune field is clearly erosive, except where the western part contacts the east jetty, where the dune field records minor sedimentation (Figs. 3; 5A). Between the 1980s and the early 2000s, the accretion rate decreased, and in certain areas, there was erosion as a result of the loss of a great deal of the dune surface due to its progressive occupation by roads, a campsite, an outdoor car park and other visitors activities. In contrast, the dunes have made progress very slight since 2001 until the present (2014), primarily on the west side (Fig. 4), with an erosive front during the storms periods.

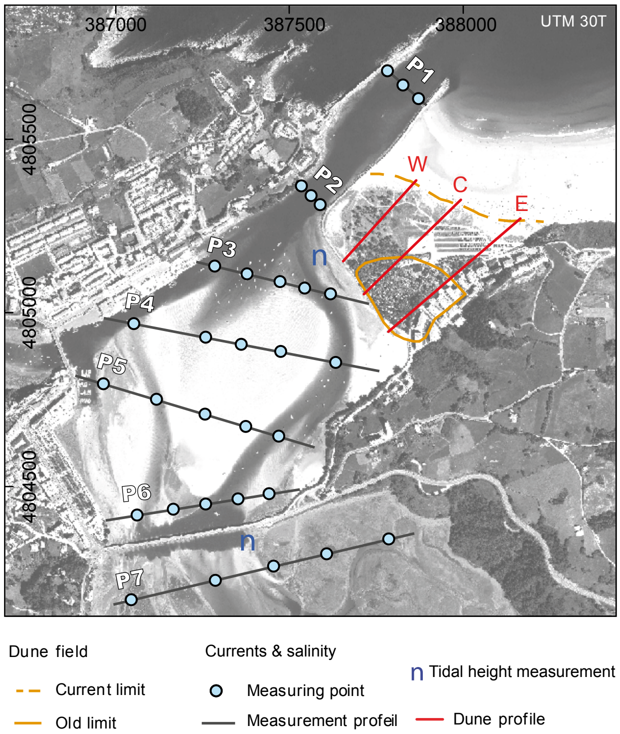

FIGURE 2. Position of profiles (P1- to P7) and stations where tidal range, salinity and flow currents were recorded in the water column. Mapping limits and measuring profiles (W,C,E) of the dune field are included.

Bay

The relatively unconfined estuary is an expansive area characterised by the predominance of sand lithologies, as in the case of the mouth zone. The outer edge of the predominantly muddy facies is located near the Maza Bridge. The bay zone constitutes a large flood-tidal delta, has an area of 617,666.99m^2, and occupies approximately one-third of the total area (Table 1). During low tide, most of the bay is exposed except the main channel. A great variety of morphosedimentary and dynamic units are generated in this zone and provide important data for the study of the 40m of sedimentary infill (Hernández Pacheco and Asensio Amor, 1966). The main channel along the east side displays a shallow bottom (<2m in spring low tides) with low sinuosity and numerous large bedforms generated as spillover lobes, by both flood and ebb tides. The hydraulic dunes or sand waves appear particularly along the margins and flat beds (Fig. 3), whereas megaripples are accessory.

The secondary channel is a minor channel connected to a lateral drainage, better developed in the western part of the bay (Figs. 3; 5B). Its role is more important during

TABLE 2. Global contrasts between river and tidal flows obtained from tide gauges (Port Service of the Spanish Ministry of Development), and the river flow data from GHESA (2005) according with Simmons (1955)

Q_F/Q_T	Maximum runoff	Minimum runoff	Average runoff
Spring tides	0.05	0.01	0.03
Neap tides	0.13	0.04	0.08
Average tides	0.07	0.02	0.04

flood tides, in which it serves as a pathway for the entry of marine water, whereas during ebb tides, the channel behaves as a fluvial outlet. Flat beds, hydraulic dunes, which mostly developed obliquely along the margins, and ripples are developed on the bottom of this secondary channel. The sand waves are of a flood type and exhibit sinuous crests; those in the southern end are of the ebb type and are approximately 10–15cm height and have wavelengths of 8–10m. Filtering mollusks as *Lutraria lutraria*, *Solen marginatus*, *Ensis siliqua* and *Pholas dactylus*, tube annelids (*Owenia fusiformis*) and echinoderms of the type *Echinocardium cordatum* colonise this unit as part of the benthic fauna (Fig. 6).

The most important structure is the flood-tidal delta, which is 720m long and has a between 534 and 250m width. This wide sandy bench cover is similar to the structures described by Hayes (1980). It displays a heart morphology in a plan view and is located between the main and secondary channels (Figs. 2; 5B). At its apex, there is a typical channel ramp of high energy, formed by currents of minor magnitude, based on the aerial photographs. The main ramp is associated very closely with the inner mouth inlet and can migrate from a more or less centred position (length of more than 350m) to another position to the west. In the least energetic areas, the sandy bottoms are colonised by *Enteromorpha spp*. and *Zostera noltii*; burrows of *Carcinus maenas*, annelid tubeworms; pellets of *Arenicola marina* and mud clasts are also present (Fig. 6). There are high-energy bedform structures represented by waves of sand with straight or slightly sinuous crests (Fig. 5B), principally along the western and central margins. Waves of major sinuosity are generated along the eastern margin. Along the contacts with the swash channel during ebb tides, cross bedded polydirectional sand waves and megaripples are produced (Figs. 3; 5B). During spring tides, the main and secondary channels ebb and flow currents display a levogyrous movement around the flood-tidal delta. The channels are eroded during ebb tides, a feature that has only been documented in mesotidal estuaries with average tidal ranges exceeding 2.50m, unlike those mentioned by Hayes (1975), which were generated under lower range conditions.

On the southwestern side, near the secondary channel, there are subplanar surfaces, referred to as sand flats. In numerous areas, these features display hard surfaces that constitute the remains of a former muddy flat. The most representative fauna consists of annelids and crustaceans (Fig. 6). On the other side, there are estuarine beaches (Los Vagos and Tostadero) consisting of sandy strips parallel to the water line and restricted to surfaces affected by the tides and, to a lesser extent, small internal waves. In association with the dredging in the 1990s, both beaches were replenished with sands from the port of La Barquera, which is located in the western part of the estuary. Behind the beaches, the backshore exhibits the development of small embryonic dunes, vegetated by *Ammophila arenaria*, formed by SW winds and additional regrowth as a result of beach nourishment (Figs. 3; 5B).

Before the construction of the jetties (Fig. 1), the distribution of the morphological and sedimentary units

TABLE 3. Morphosedimentary and dynamic units of the San Vicente de la Barquera estuary

Estuarine zones	Morphosedimentary and dynamic units
Mouth complex	Sand inlet (rectilinear) Ebb spill over lobes Sand confining external barrier: beach/dunes system (two generations of dune fields)
Sand Bay	Main channel Secondary channel Flood-tidal delta Flow and ebb spillover lobes Sand flats Sand flats with *Zostera* Sand estuarine beach Estuarine dunes Tidal creeks Mud-sand flats
Tidal flats	Main channel Ebb and flow spill-over lobes (main channel) Ebb spillover lobes (tidal channel) Mud flats and marshes of *Enteromorpha, Zostera, Sarcocornia, Spartina, Halimione, Juncus, Phragmites.* Tidal creeks Ponds Anthropic marshes
Upper channel	Gravel and pebble main channel Gravel and pebble longitudinal bars Anthropic fluvial-tidal flats

was different, and the current secondary channel may have served as the main channel. After the jetties were constructed, the flood-tidal delta and channels migrated to SE, resulting in the present configuration. The main flood-tidal delta ramp was oriented facing the inlet due to the channelling of high-energy currents caused by these two structures during flood tides. The secondary channel is inactive during low tides, whereas formerly, it channelled the currents during the rising and falling tides.

Tidal Flats

The tidal flats constitute the largest area of the estuary with high organic productivity. Their areal extent consists of 3,560,453.34m^2 (Table 1) of the Rubín (Escudo) subsystem and the 1,278,938.02m^2 of the Pombo subsystem. These zones are dominated by natural mud flats, including marshes, which are colonised by certain halophytic plants (Ibáñez *et al.*, 2009) and many annelids and filtering bivalves (Fig. 6). Their inner portions have been intensely altered by planted eucalyptus trees and reclamation for pastures and other agricultural use (Table 1). The main channel and tidal creeks are highly modified by the construction of marine aquaculture facilities and small dikes. Presently, 27.69% of the mud flats have been anthropised for aquaculture, forest or agricultural uses.

Estuarine dynamics

Water mixing

San Vicente is a predominantly mesotidal estuary in which the river input is relatively minor. A comparison of the tidal and river flows indicates that the estuary is well

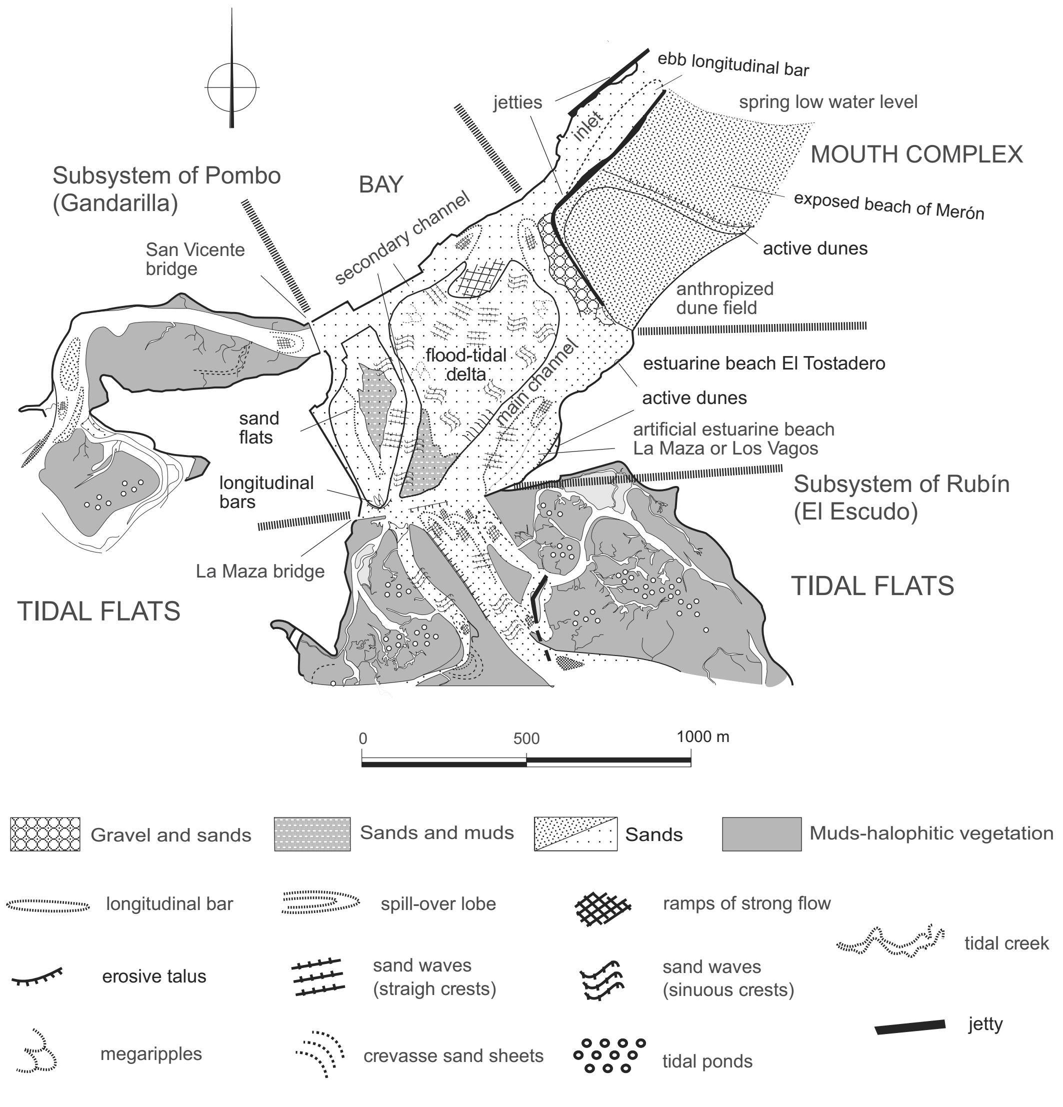

FIGURE 3. Geomorphological zonation and principal morphosedimentary and dynamic units, including the most important large scale sedimentary structures.

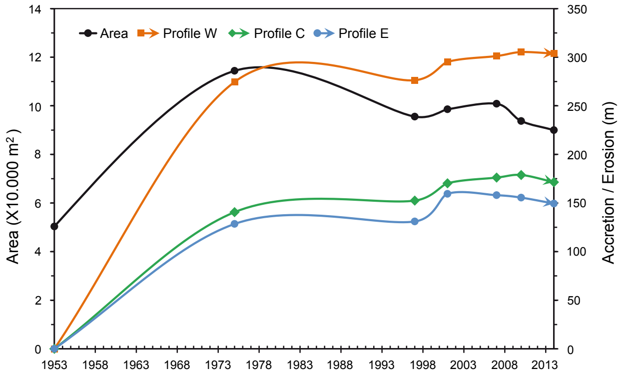

FIGURE 4. Evolution of Merón dune field between 1953 and 2014. The black line represents the dune field area from the jetty construction date until the most recent photograph. The gray dashed lines indicate accretion and erosion in each profile (west, center and east). The vertical dashed lines correspond to the aerial photographs used.

mixed or vertically homogeneous (Cameron and Pritchard, 1963) in practically every the cases examined (Fig. 7). This was determined by applying the criterion of Simmons (1955) modifying the numerical limits of the flow ratio: 0.01–0.10 (vertically homogeneous), 0.10–1.0 (partially mixed), and >1.0 (highly stratified). All values are less than 0.10, except during neap tides and maximum river flows, when a slight tendency toward partial mixing was identified in the tail (Table 2). The surficial waters are generally very saline to brackish throughout the water column (Figs. 7; 8), except where the fluvial channel empties and during low tides. The isohaline distribution is related to the intrusion of seawater and freshwater discharges and to segregation between both estuarine margins due to the Coriolis effect (saltier water entering through the western margin). The salinity gradients are always very low, especially during high tides. During low tides, the waters are confined to the main channel and certain tidal creeks.

Currents

A simplified dynamic model during the four stages of a tidal cycle, including the primary water movements, is shown in Figure 8. The most complex flows of water occur in the outer estuarine area, where strong currents are responsible for the development of large sand structures, *e.g.*, in the inlet, flood-tidal delta, and main and secondary channels. Consequently, the sand fractions of the bottom sediments are involved because they are mobilised by the strong currents (>0.5m/s).

During low tides, the estuary functions as a river because the water-salt mixture predominantly flows undirectionally through the main channel and the tidal creeks. Stronger currents were measured in the surface of the mouth, the main and secondary channels (0.5m/s), in contrast to the rest of the bay that is covered by thin water (Fig. 8A). However, the secondary channel, between the flood-tidal delta and the port, carries flowing water from the Pombo subsystem, which is opposed the flow of the flood tide, and therefore, slows the intrusion of salt water.

From low tide until half rising tide (Fig. 8B), salt water penetrates the inlet mouth and tends to flow upstream through the channels. Particularly, during spring tides, there are two overlapping bodies of water in the inlet. The bottom water, which is denser, creates higher water velocities from the SE inlet side to the S and SW. When the bay is being flooded, the flood-tidal delta is activated, and the strong and moderately concentrated stream on the ramp is converted to unidirectional currents to the SW and SE (0.5–0.75m/s), dissipating it centrifugally downstream, until they affect the entire delta. Strong bottom currents are dominant in this tidal stage and cause

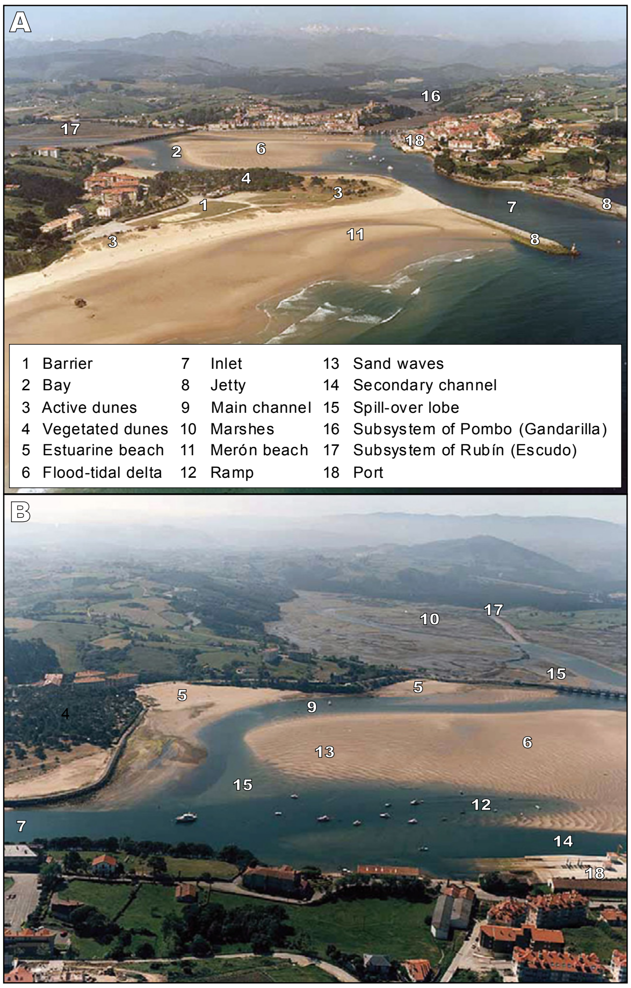

FIGURE 5. Oblique aerial views of the estuary, indicating the different units and structures present. A) Mouth with the beach/dune system, the jetties with the inlet and the bay in the background. B) Great part of the bay, the vegetated dunes and the Rubin subsystem.

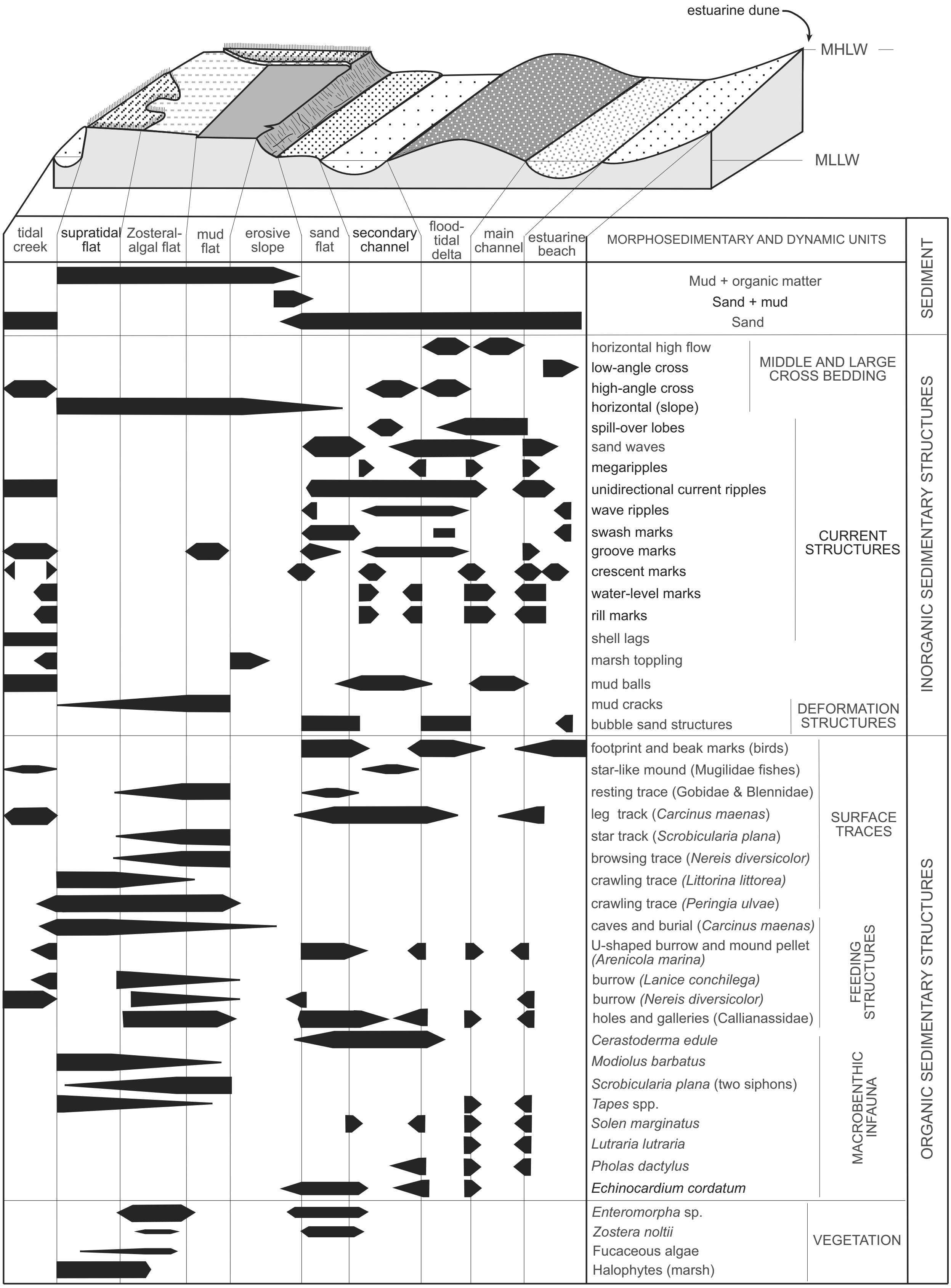

FIGURE 6. Distribution scheme (unscaled) of the most important sedimentary structures in the morphosedimentary and dynamic units of San Vicente de la Barquera estuarine bottom.

some enlargement of the flood-tidal delta to the SW. This delta asymmetry is controlled by the NE–SW orientation and great length of the lateral jetties, which send toward the bay strong flows that require space to be deflected to the SE by the Coriolis effect. Clearly, the inner areas of the bay are drained by mixed water in the main and secondary channels and also the spill-over lobes are activated.

The salt water filling continues during the high tide (Fig. 8C), enhancing the flood-tidal delta. A weak surficial current (1m deep) flowing counter-clockwise is generated (<0.25), resulting in a reworking of the tidal delta geometry, smoothing the contours and keeping its main heart shape. At half falling tide (Fig. 8D), the estuary empties mainly by the channels where the higher energy levels are developed, gradually destroying the above mentioned current distribution. The ebb spill-over lobes are activated during this phase and in the rest of the estuary are associated with reduced ebb currents. Despite this general tendency, a minor amount of intruding seawater still flows below the less-dense mixture.

Hidrodynamic and sedimentary model

Hydromorphologic data are the key to the understanding of the estuarine dynamics, although these systems are always influenced by the salinity (Elliott and Whitfield, 2011). This section presents the trends of the processes involved as reflected by the currents, taking into account the presence of the two distinct subsystems, the Pombo and Rubín, which lead into the bay (Fig. 9), as in the Eo estuary (Flor *et al*., 1992) and the Guernica estuary (Flor and Flor-Blanco, 2006) in Spain, and the Mondego estuary in Portugal (Cunha and Dinis, 2002). This dynamic simplification allows the understanding of the sediment distribution and provides a coherent explanation for the origin of the barrier, the way in which exchange occurs in the mouth through the inlet, and the morphology of the central flood-tidal delta, not forgetting the importance of the wind and waves in the estuary in the development of various estuarine beaches and dunes, and the anthropogenic influences.

As in any estuary, several dynamic processes are involved in the movement of water bodies, as are the salt mixtures and fluvial flows and the effects of wave impact near the mouths and their intrusion into the estuary. In this estuary, tidal dynamics, together with the waves and a nearly negligible fluvial action are important in the sediment remobilisation. The prominent role of wind activity is important in the formation of the confining barrier dunes (N winds), while the formation of the estuarine inner dunes is due to SW winds. Furthermore, tides act through the marine flooding of the estuarine valleys, but the geometry of the mouths determines whether tidal or wave processes are of greater relevance.

The average fluvial watershed discharges of both subsystems are low. In the case of the main arm the Escudo river, it is 4.71m^3/s (Confederación Hidrográfica del Norte), which may indicate that the continental sand imputs are practically negligible. The beadload fraction, mainly siliciclastic sands, comes from the western rivers (Deva and Nansa) with significant water flows. The majority of the contributions from both rivers were displaced by littoral drift to the east before the Holocene eustatic recovery, being carried into the estuary by tidal currents and waves.

In the Merón (the beach barrier), littoral currents caused sediment drift to the west by wave refraction, facilitating sand accumulation alongside the eastern area of the jetty, which encloses the beach-dune system, the bar mouth and the inlet. While the northern storm-induced waves causes front dune erosion, during periods of calm there is sand deflation within the limits of the dunes and the flow currents move against the west margin. The opposite margin is influenced by ebb currents during low tide and half falling tide. The evidence is the presence of the well-defined longitudinal ebb bar connected to the right jetty (Fig. 9). During the half rising tide, the water is introduced with great energy through the inlet into the flood-tidal delta in the centre on the bay. Strong currents and sand sediments from the ramp are distributed through the bottom in a centrifugal mode generating a heart geometry, which is helped by the incoming waves in certain circumstances. All of the flood currents flow through the channels surrounding the sand shoal, but they mostly flow through the western (secondary) channel and hugging the bottom of the eastern (main) channel, which always contains water of the Rubín ebb current. This flow is most prominent during high tides and spring tides, when it develops a counter-clockwise movement of low intensity in the first upper meter of the water column due to the Coriolis effect, while the rest of the bottom water is moving strongly upstream. This phenomenon takes place before and after spring tides, so that the main channel empties ebb currents including the river flow, and the secondary channel drains in the opposite direction. The semi-round appearance of the tidal flood-delta is typical of estuaries with a wide bay and a high mesotidal, range than low mesotidal, that are more complex as reported by Hayes (1975).

The estuarine beaches are restricted to the eastern margins of the bay because the residual external waves and internally formed waves during high tides result from the action of NW winds. NE winds are not significant because its fetch is not long enough to allow waves of enough energy. In addition, the port situated in the west of the Bay prevents the sedimentation. Winds from the S which may be intense and frequent during certain periods of the year,

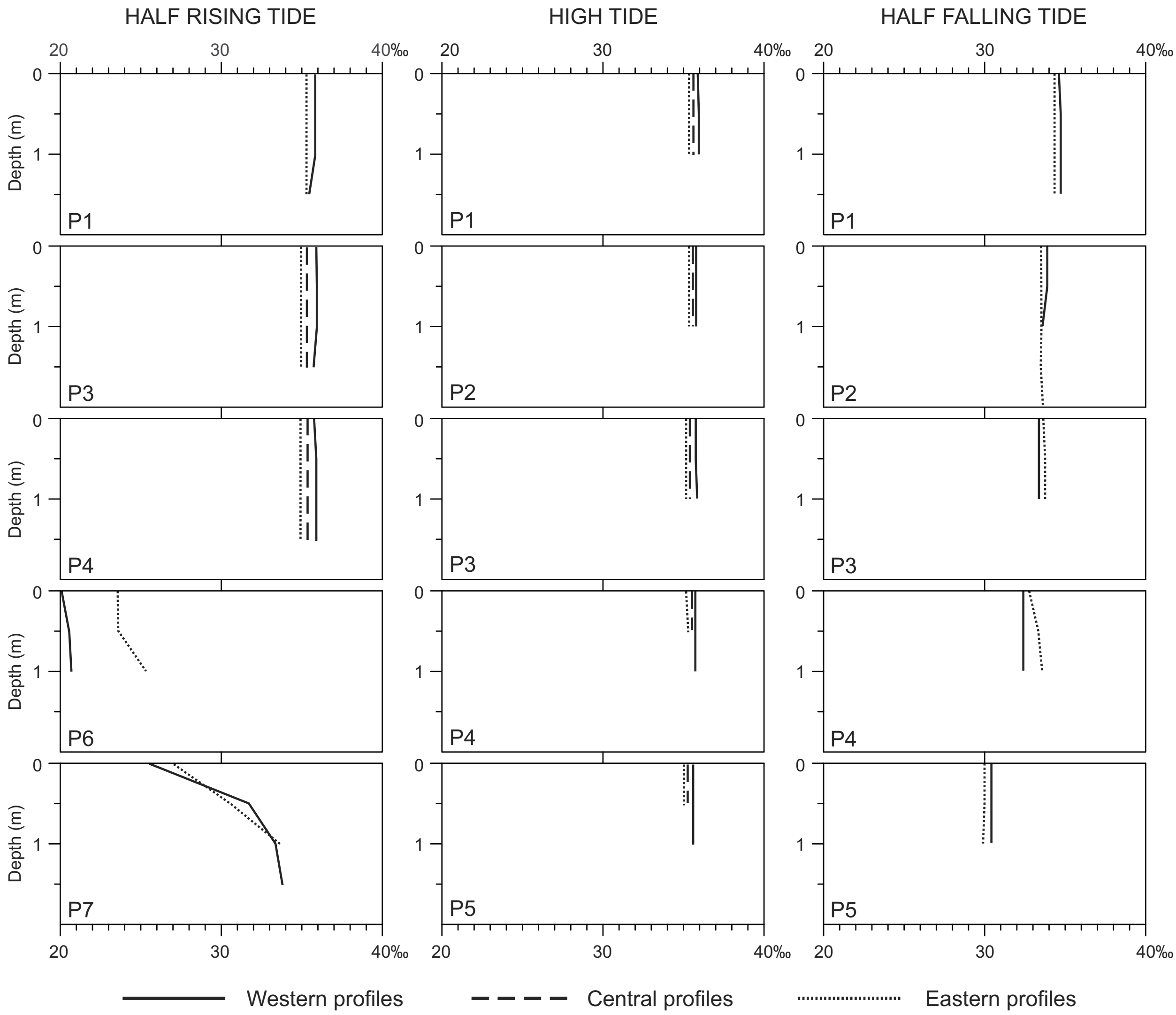

FIGURE 7. Vertical salinity records from the surface to the bottom (west, central and east) at three tide phases: half rising tide, high tide and half falling tide, for the profiles selected in the estuary.

do not significantly affect the development of the beaches, because are protected them. The eastern jetty and the dump of the material dredged from the inlet on the estuarine beaches, have clearly changed the estuarine morphology.

In the southernmost part of the study area, *i.e.*, in both arms, the tidal influence is the most considerable (flood and ebb tide) because the Escudo and Gandarilla flood flows are very low. Thus, for the most part, the water moving across the mud flats varies from the salty marine water to the brackish water stored during the previous flood tide.

DISCUSSION

San Vicente de la Barquera estuary can be considered as a wave-dominated estuary (Dalrymple *et al.*, 1992) with four geomorphologic zones clearly defined from the mouth to the inner limit (Flor, 1995). According to Pritchard (1967), this estuary could be classified as a bar-built as it is controlled by morphological aspects The tidal range mostly controls the geometry of the area of the river mouth, *i.e.*, preferentially outside rather than inside the area of confinement. This arrangement allowed Hayes (1975) to classify this mesotidal type of estuary as a confined system, in which large sandy structures such as a flood-tidal delta, estuarine beaches and dunes are developed within the system. From the geomorphological point of view these systems correspond to estuaries confined by a barrier (Fairbridge, 1980) where only the exposed beaches are dominated by incoming waves and its aeolian dune field is generated by winds from the seaward. According to the work of Valle-Levinson (2011), the San Vicente estuary may be considered primarily as a sand bar-built estuary

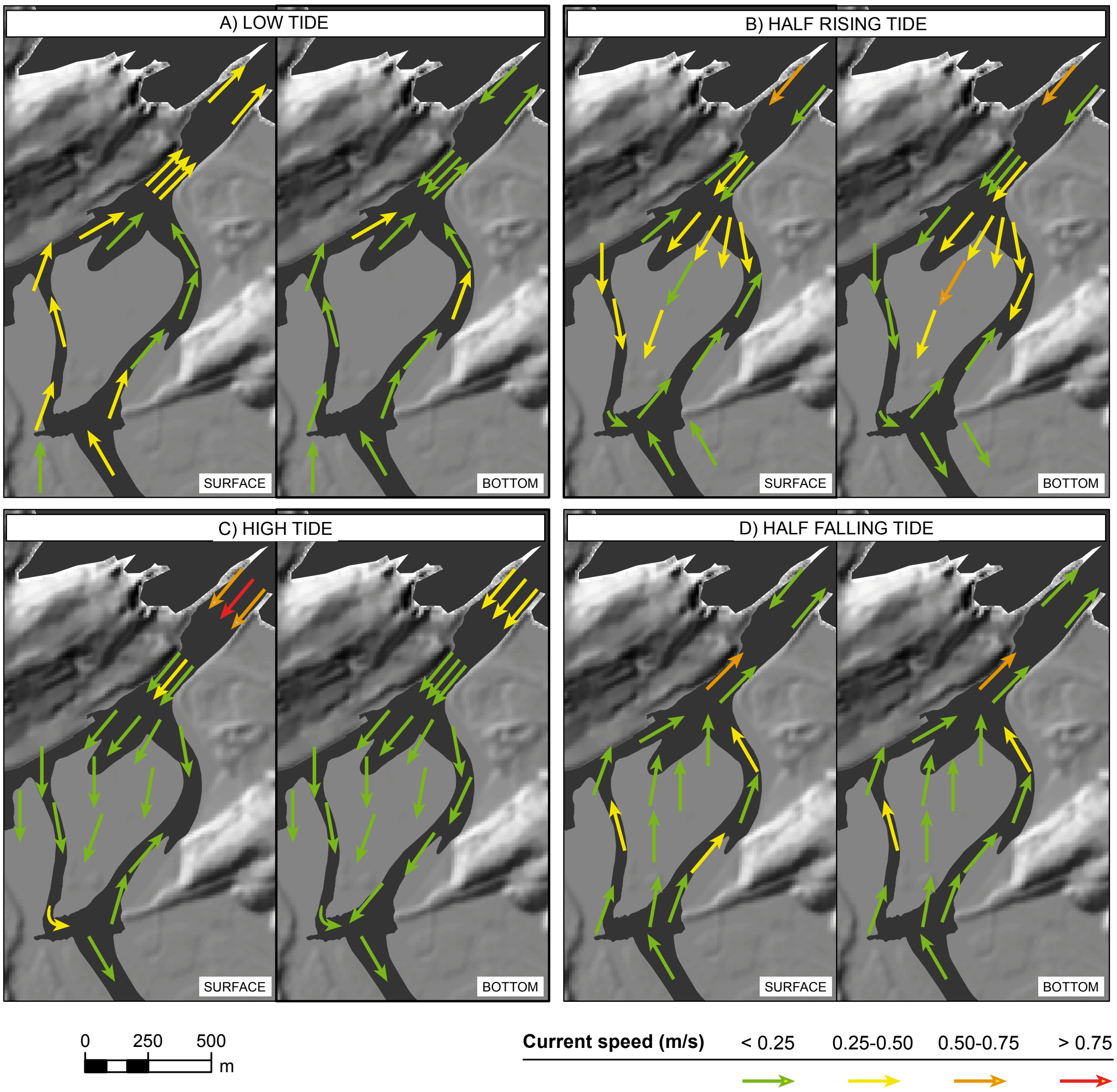

FIGURE 8. Simplified scheme of currents during a tidal cycle (spring tides and low fresh water discharge).

but with certain dynamic aspects of tectonic estuaries, based on the presence of gravitational circulation as well as its origin and geomorphology. This barrier involves landward-migrated foredunes, backshore dunes, and associated aeolian sand sheets derived from the backshore and foreshore zones, similar to a dune field barrier (Otvos, 2012).

Regarding the anthropogenic impacts on the system, the confining barrier is where the most significant changes have occurred. There, the dune field (relict dunes in the inner part) has migrated considerably by the progradation of the set of active dunes due to inlet channelling. In this case, as pointed out by Flor-Blanco *et al.* (2015), the stages of the anthropisation model are 3c and 3d (by parking areas and urbanisation, respectively). Since 1944, the year of construction of the jetties, there has been a significant development of the dune field, which prograded northward until the 1970s and then experienced a gradual loss due to the anthropogenic colonization and the beginning of the erosion. For this reason, a coastal policy involving the outer active dune field was established to avoid the continued erosion observed at the start of the 21st century. Since the construction of the jetties, the dune system has prograded between 305.7m (W) and 162.5m (E), which is equivalent to 4.63m/yr and 2.46m/yr, respectively. However, two historical storms in the winter of 2014, with waves of up to 11m, triggered the front dune recession from 0.50m in the west to 7.35m and 6.10m in the center and eastern part, respectively. This destructive event affected the Cantabrian coast all along (Flor *et al.*, 2014).

The modification of an external inlet by jetties is an important change in the morphology and dynamics of a mouth-barrier beach, triggering changes in a small period of time (Flor-Blanco *et al*., 2015), that allow for faster flow and thus, preventing the formation of sandy bottom bars. The beach-dune system then, progrades until it stabilises and creating a new confined area. This solution has often failed (Pietrafesa, 2012), resulting in costly channel maintenance by continuous dredging (Díez, 2001). One of the most important processes that occur in this estuarine confinement is the westward littoral drift on the beach that carries most of the sediment in the intertidal zone as a result of the refraction (Duck *et al*., 1995). On the other hand, there has been only maintenance dredging in the fishing port (western side of the Bay) involving dumping of the spoils into the system (estuarine beaches of the eastern side) or within the cell sediment without exceeding the depth of closure.

Another part of this study involve the measurement of the currents over tidal cycles, which are responsible for the formation of bed structures. They are associated with large ebb and flood-tidal deltas and connected with the artificial inlet, similarly to tidal lagoons (Stive and Wang, 2003). In this case, the most important structure is the sandy flood-tidal delta, which occupies much of the bay and formed primarily during flood tides until the high tide (Fig. 9). Detected by field surveys, the Coriolis effect is the main responsible for its heart-shape as a result of the laevorotatory circulation during the high tide. This counter-clockwise rotation registered in this estuary has also been measured in other systems, for instants, in the Pará estuary in the Amazón by Da Silva Gregório and Mendes (2009), in the Wadden Sea (Netherlands) by Elias *et al*. (2012), and in the Mondego estuary (Portugal) by Cunha and Dinis (2002). Other representative estuaries with similar morphological features and sediment distribution are the Dyfi estuary (Salas-Monreal *et al*., 2009; Brown and Davies, 2010) and Oualidia lagoon in Morocco (Hilmi *et al*., 2005).

When the water depths at the channel increase as a consequence of dredging, the saltwater intrusion in tidal estuaries increases, and the bottom water is (partly) saline or brackish over substantial lengths (Kuijper and Van Rijn, 2011). This phenomenon may be the cause of further development of high-energy bedforms in the central flood-tidal delta, which was already present before the inlet modification. Also important is the fact that the broad salt marshes were reclaimed in the first

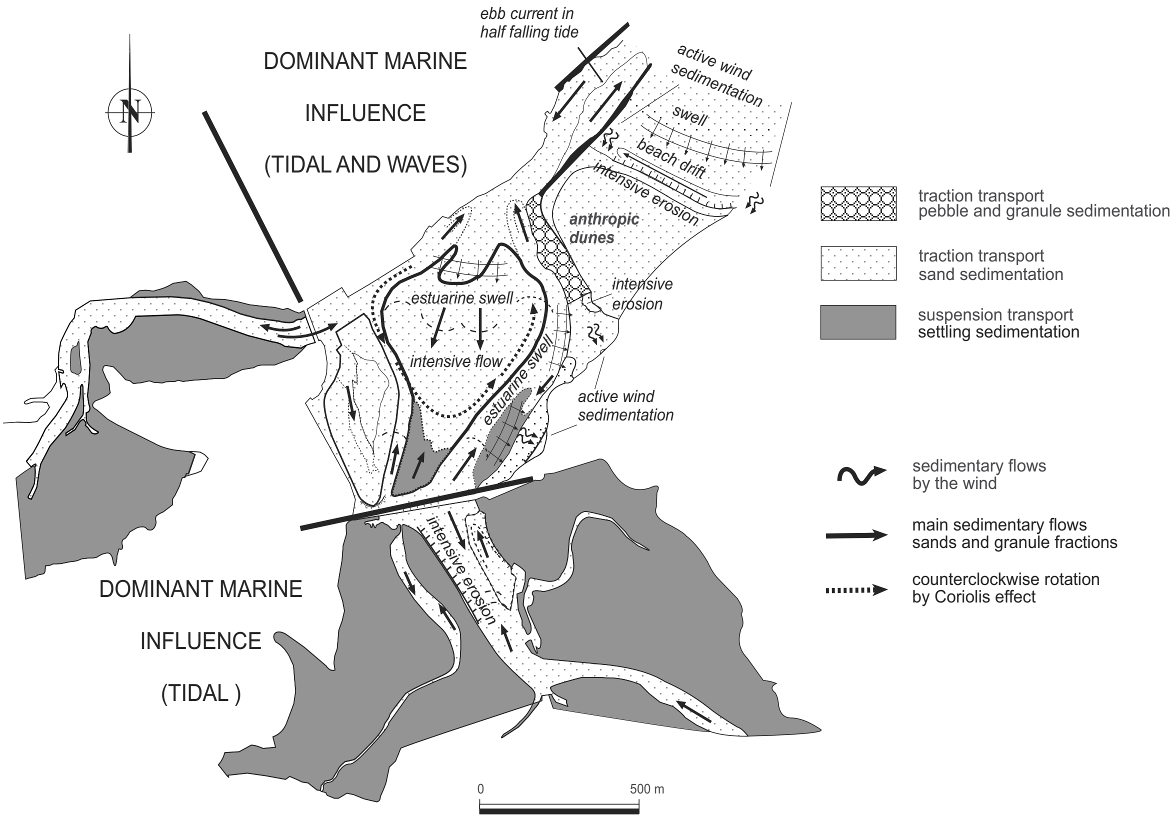

FIGURE 9. Dynamic and sedimentary processes model in the estuary of San Vicente de la Barquera, establishing the limits of the dominant influences of marine and continental agents.

half of the 20th century and used for urban development and agricultural production. This conversion favoured tidal current circulation, causing a drop in the water table that triggered pyrite oxidisation processes (Fernández *et al.*, 2010).

Taking into account the current sea level rise scenario and that the major sand contributions come from the neighbouring estuaries of Tina Mayor and Tina Menor (Flor-Blanco and Flor, 2008), it may be predicted that the sediment will be moved upstream, infilling the inner areas (Bruschi *et al.*, 2013). For this reason, the estuarine system will become unbalanced because the rate of sediment input will not be sufficient to match the rate of sea-level rise, and the system will reach a new state of dynamic morphological equilibrium (Van Goor *et al.*, 2003). According to Cowell *et al.* (2003), when the sea level rises, the accommodation space becomes positive, and sediment may be imported. Note that this process is occurring in the studied estuary, where the bay is being filled and the northern part of the Rubín marshes is characterised by the presence of fine sand. The rise in sea level has been studied worldwide, with predictions for the Iberian Peninsula at rates of 1.9±0.3mm/yr (Leorri and Cearreta, 2009), similar to those of Alonso and Pagés (2010), with a rate of 2.0mm/yr or a regional rise in sea level of 2.08±0.33 mm/yr during the period 1943–2004 (Chust *et al.*, 2009).

The northern part of the Rubin channel is totally infilled by sand, whose morphological variations (filling trends and outward/inward migrations) may be attributed to the combination of moderate sea level rise and the availability of sediment from the adjacent coasts (Van Goor *et al.*, 2001). The question is how these trends will affect the environment, in as much as estuaries are favoured sites for urban, port and industrial activities and the anthropogenic pressures emanating from the catchment and marine environment, which affect estuarine morphology, sedimentary or dynamics, or all three at the same time. It is thus likely that estuaries will incur more pressures than other systems (McLusky and Elliott, 2004).

CONCLUSIONS

An study of the development of the main structures of the San Vicente de la Barquera estuary has been carried out, with a particular focus on the sandy flood-tidal delta, which is present in many Cantabrian estuaries. Based on the gathered data, we conclude that this estuary is a mesotidal, weakly stratified or vertically homogeneous estuary with hypersynchronous behaviour, in which marine influences dominate over the fluvial ones, despite the sheltering effects of two rivers.

This work shows that the construction of two jetties in the 20th century modified drastically the morphology of the estuary, triggering the rapid, pronounced progradation of the dune field between 275m and 140m until 2010, leading to foredunes (<2m) and tabular dunes. At present, the front dune field is erosive during storm periods and was highly affected by 2014 storms.

The construction of the jetties has also encouraged the migration of large bay bedforms to the SE and the orientation of the main ramp of the flood-tidal delta. This phenomenon is indicated by the introduction of sediment that occupied the space before the jetty and it was present until the stabilization of the mouth. Regarding the dynamics, the high currents associated with the rising tides are critical: once these currents pass the artificial confinement, the flow is dissipated building the flood-tidal delta with a strong component to the SW (0.5–0.75m/s) elongating this shoal and centrifugally distributes the flow inward. Only during high tides, primarily during spring tides, a Coriolis effect with low velocities (<0.25m/s) facilitates a counter-clockwise rotation in the upper surface reinforcing this heart-shaped structure.

At present, the estuary is in a state of morphological and dynamic stability, therefore major modifications as the enlargement of the jetties or further occupation of the dunes, are not recommended. On the other hand, the dredging of the secondary channel and the inlet, and the subsequent dumping over the estuarine beaches has not caused a sediment deficit as the sand is gradually returned to the system.

In summary, the importance of the understanding of estuaries for their management cannot be overlooked since estuaries are ecosystems that cannot function indefinitely on their own in isolation and depend largely on other ecosystems. This study enhanced the understanding of this type of systems, so sensitive to any modification by natural processes and human intervention, and the results obtained will be of relevance for the development of management policies in anthropised areas, in accordance with the recommendations of the European Directives of Habitats Conservation (Gracia *et al.*, 2009).

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