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Dynamics and morpho-sedimentary interactions in the lower mesotidal estuary of Villaviciosa (NW Spain): A management proposal

G. FLOR[1] G. FLOR-BLANCO[1] J. REY[2]

[1] Department of Geology. GeoQUO Research Group. Geomorphology and Quaternary, University of Oviedo
Arias de Velasco, s/n. 33005, Oviedo, Asturias.
E-mail: gfb@geol.uniovi.es

[2] Esgemar, S.A. Estudios Geológicos Marinos
Local M5 frente al Muelle 7, Puerto de Málaga, 29001, Málaga.
E-mail: jjrey@esgemar.com

ABSTRACT

The accumulation of sediment in the mouth of Villaviciosa estuary (NW Spain) is becoming an obstacle for the safe navigation in this estuary. One sector of its outer inlet is characterised by a broad shoal linked with a longshore bar of a beach, whose erosion is causing the silting of this area. On this basis, this paper aims to describe the processes that occurred in the lower part of the estuary due to the anthropogenic activities in the channel and inlet. For this purpose, several measurements were made in the water column and in the sedimentary bottoms to characterise the processes that occur in this area. Based on these results, a dynamic and morpho-sedimentary model was developed to examine the interactions between the lower estuary and the exposed part of the confining barrier beach, which allows to establish the evolutionary trends of sedimentary bottoms linked to the marina of El Puntal. Different management measures are carried out to reduce the impact of the sediment accumulation on the navigability, such as periodically dredging in the inlet of the estuary, and the subsequent dumping of the sediments in areas near to the closure depth. Consequently, future retreat of narrow inlet and sandy shoal can be avoided, maintaining the sedimentary volume in the system.

KEYWORDS **Longshore bar. Dynamic and morpho-sedimentary model. Inlet. Management. Villaviciosa estuary.**

INTRODUCTION

Many estuaries in the north of the Iberian Peninsula (Cantabrian Sea) and elsewhere that host commercial fishing ports and/or marinas, represent important economic assets and should maintain the environmental quality (De Vriend, 2003). Most of these, contain larger ports which should be frequently dredged, and, consequently, regulations have been developed as an appropriate sediment management tool (*e.g.* the Fraser River Estuary: FREMP, 2006). Dredging and filling activities may produce deleterious effects and few benefits, particularly in regard to biological functions and water quality (Johnston, 1981). These activities constitute an environmental risk (Carvalho *et al.*, 2001) whose impacts depend on the methods used, the quantity and characteristics of the sediments, local hydrology and seasonal effects (Newell *et al.*, 1998). Studies of morphological changes have been conducted, some include historical documentation about the construction of jetties (Watts and Zarillo, 2013). The knowledge of estuary dynamics can be applied to coastal resource management (Ryan *et al.*, 2003; DEFRA, 2009) and can help to build a conceptual framework for the protection of estuaries (Kingsford *et al.*, 2005). There are some interesting articles about anthropogenic modifications in the estuaries (Cooper, 2003, Dabees *et al.*, 2008; Nordstrom, 2013; Flor-Blanco *et al.*, 2015) and some authors consider that increasing human use will influence the coastal zone and estuaries in the future (Flor and Flor-Blanco, 2005; Wolanski and Ducrotoy, 2014). Several studies have assessed impacts of dredging on the maintenance of the outer sand inlets and the changes that dredging causes in bottom morphologies and hydrodynamics (Morales *et al.*, 2004; McFadden *et al.*, 2007; Rodríguez-Ramírez *et al.*, 2008). Also, there are natural events such as an increasing sea level that could affect the coastal zone (Hadley, 2009).

The Ports Service of Asturias manage 24 small ports, some within estuaries, with the goal of improving facilities or creating new port precincts. In the first third of the twentieth century, many Asturian estuaries were transformed, mainly the mouth areas, and jetties were constructed. In recent years, the authorities, especially regional ones, have opted for the development of marinas that, in the case of Asturias, coexist with inshore fishing activities.

The dredging in the Villaviciosa estuary was performed to deepen and widen the marina with an interval between dredging events of more than 15 years. The amount of sand dredged was relatively small and has been extensively studied, by Flor-Blanco and Flor (2009) and Flor *et al.* (2013). In this case, the most interesting feature is a great shoal generated by the western drift current beach, which is scoured by the outer inlet due to the jet flow.

Consequently, the aim of the study is to show a knowledge model which links the dynamics with morphological features and sediment distributions, which serves as a tool for designing, or planning port and channel dredging strategies or activities. The knowledge of these systems can be used to apply solutions in the future management of the marina and channel which does not affect the fishing, tourism or surf activities.

STUDIED AREA

The study zone is situated in the eastern cliff coast of Asturias (NW Spain), concretely in a protected nature reserve: Reserva Natural Parcial de la Ría de Villaviciosa (Decree 61/95, established April 27th, Principado de Asturias Government). It is also designated as a SCI (Site of Community Importance) and a SZBP (Special Zone of Bird Protection) of European Nature 2000 (Fig. 1).

This estuary is confined by a bar-built and sheltered by a broad sand spit. It has a funnel shape that is narrow and very elongated along a 9.84km stretch (the inner limit of the tide wave), pointing mainly in the NE–SW direction. It covered an area of 860.34ha before the execution of an extensive marshes reclamation project, the aforementioned artificial channelling of the marina and the construction of other docks upstream. There is a maximum width of 1,130m in the outer estuary between the marina of El Puntal and the eastern side of Misiego the maximum width is 200m and the main channel and inlet extend 1600m, with an average width of 130m.

The fluvial excavated valley is composed of Permotriassic sedimentary rocks (quartzite conglomerates, sandstones and salts) and Lower Jurassic rocks (limestones and dolomites). A large NE–SW fault is located on the western side (Beroiz *et al.*, 1972; Pignatelli *et al.*, 1972). The soft easily erodible materials in the valley allowed an increasing width of the estuary (Flor *et al.*, 1996). The estuary is drained by the Linares coastal river (basin of 163km^2), that has a very small watershed and little freshwater input. According to Álvarez (1971) and García (1972), the annual average runoff is 3.36m^3/s. Within a 12-hour tidal cycle, the amount of fresh water entering the estuary is 0.256×10^6m^3.

As a result of the fluvial down-cutting along the Tertiary Range (Cantabrian Range), great trunk rivers were the active continental agents supplying sand and mud-based siliciclastic sediments to the coast.

REGIONAL SETTING

In the study area, more frequent incoming swell waves come from the NW, and N and NE. There are significant waves less than 2.0m, and the periods between waves range from 8 to 12 seconds (Puertos del Estado. Spain). Local morphological waves were measured (Table 1), and the bathymetric distribution in the offshore zone of the Rodiles beach shows a beach drift from E–W with weak intensities varying from 0.1 to 0.3m/s in the exposed beach. The waves carry beach sand from the beach to the mouth of the estuary.

Tides are semidiurnal and mesotidal (ranging from 1.0 to 4.65m), and according to data gathered from 1995 to 2004 in Gijón Port, the average range was 2.72m. The estuary is a hyposynchronous and vertically homogeneous type (Table 2) because fluvial discharges are low, but it is highly seasonal, with the maximum freshwater inputs occurring in autumn and spring. Thus, well mixed estuarine conditions occur only when river flows are high; during spring tides the estuary is partially mixed (Flor *et al.*, 1996).

Winds are strongest in the SW and W directions and weakest in the NW and NE directions (Felicísimo, 1992). The NW and W winds generated broad aeolian dune fields

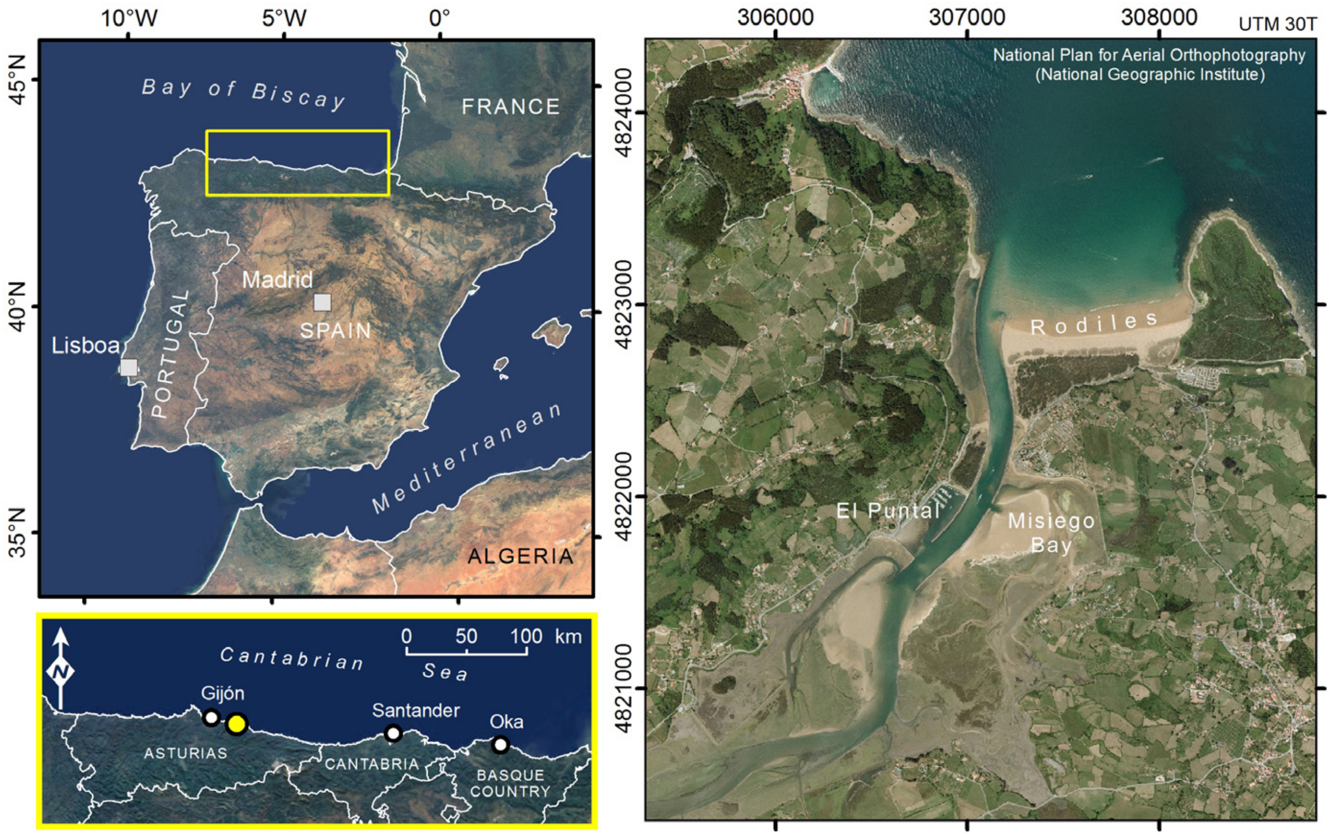

FIGURE 1. Situation of Villaviciosa estuary in the NW of Spain (Iberian Peninsula, Bay of Biscay).

on the exposed beach, and NW, SW and W winds are indispensable for building estuarine dune fields in Misiego Bay. Only approximately 15% of the winds had velocities of 18km/h, and maximum wind gusts were 166km/h between 1980 and 2010 (data obtained from AEMET in the Asturian airport. http://datosclima.es/Vientostad.php).

METHODOLOGY

Only aerial photographs that were taken during low tide were used: 1945 and 1956 (US Air Force), 1970 (Diputación de Oviedo) and 2007 (Cartographic Service of the Principado de Asturias). These photos provide historical information to establish the major changes and reveal the more stable areas. Recent satellite images from Google Earth were used to record the emerged areas because these images were taken at mid-tide. These aerial photographs, in addition to the topography, were georeferenced by a rubber-sheeting process using checkpoints based on current vector maps in ArcGis 9.3 (ESRI Inc).

Some techniques were applied to the topography of the emerged beach and aeolian transition belt, with a Leica Geosystems, ATXGPS 900 model (GPS-RTK station linked to the National Geodesic Red). The bathymetric data was collected using an Ecosounder monohaz bifrequency 24–200kHz Odom Echotrack, and bathymetric curves were generated at 0.5m intervals. Geophysical studies were conducted with high resolution continuous reflection seismic monitors (bottom Perfilator 3.5kHz) with an instrument ORE of 10kW. Perpendicular and parallel profiles were obtained in the open area, and many transverse profiles were obtained in the channel (Fig. 2). A wide side sonar (GeoAcoustics 100/500kHz) was used for imaging the bottom, with an image resolution of 0.20pixel/m. Only two profiles were taken along the central belt of the channel, from the marina of El Puntal at the inlet crossing to the North where the depth was 10m.

Data on the mixing of waters and currents was obtained from the salinity (‰) with a YSI 556 MPS multiparameter

TABLE 1. Significant heights and periods of the local morphological waves in the mouth of the estuary

Wave paramenters	NW	N	NE
Hs (m)	2.57	1.68	1.72
Tp (s)	11.54	9.41	7.11

TABLE 2. Relation between fluvial (QF) and tide volumes (QT) of fresh and salt waters, respectively, under extreme and average conditions, following Silverster (1974) criteria

Q_F/Q_T	LOW RUNOFF	FLOOD	AVERAGE
NEAP TIDES	0.004	0.082	0.049
SPRING TIDES	0.001	0.833	0.012
AVERAGE TIDES	0.002	0.000	0.020

device, and the velocity (m/s) and direction of currents were recorded with a General Oceanic, Inc., Model 2035-MK III current meter. With this equipment and using a boat, four profiles were fixed along the channel area. Three stations were used through the entire water column, at 0.5m depth intervals up to a maximum depth of 4.50m (Fig. 2). Four representative tidal intervals were approximately 1.5 hours chosen in a spring cycle tide: high tide, half falling tide, low tide and half rising tide (Flor *et al.*, 2013).

Additionally, 20 bottom sands were sampled with a Petersen drag along the channel, and shallow areas were sampled around the inlets (Fig. 3). The samples were washed and dried, and 100g of each sample were placed in a set of sieves at 0.50ϕ intervals from -1.5 to 4.0ϕ using electromagnetic and digital sieve shaker (CISA) for test sieves of 200mm Ø, and weighting the result in a precision balance. Grain-size distributions were plotted in a probabilistic cumulative curve, and textural statistical parameters (mean, standard deviation, skewness, and kurtosis) were calculated according to Folk and Ward (1957) method and the GRADISTAT programme (Blott and Pye, 2001). Siliciclastic and carbonate content (%) were measured using a Bernard calcimeter, according to the method described by Vatan (1967).

The most interesting textural parameters are the average main size and sorting because these parameters are directly related to energy level, sand sediment transport and the resulting topographic geometries. Carbonate content also provide good information, as it is closely related to the average grain size (a higher percentage of carbonate implies higher average grain size and more energy).

RESULTS

Morphology

Topographic and bathymetric data, collected at 0m in the Gijón port, were integrated into a detailed map (1/5,000) of the Cartographic Service of the Principado de Asturias (Fig. 3).

From a morphodynamic point of view (Short, 1999), the Rodiles beach corresponds to a dissipative embayed beach (when storm waves occur) of 1km long, that is sometimes intermediate barred beach with a low-tide terrace (a slip-face ridge as a subtype of intertidal near-shore bar according to Wijnberg and Kroon, 2002) during summer or calm conditions. This complex barrier has developed two associated dune fields; the external one was generated after the channelisation was completed in 1925. The inlet is located in the western area, a narrow channel that extends freely until it reaches the submerged mouth bar (or terminal lobe, according Hayes, 1980), that connect to the ocean; typically, they occur in those estuaries that have a plentiful supply of sediment (Wright, 1977); and

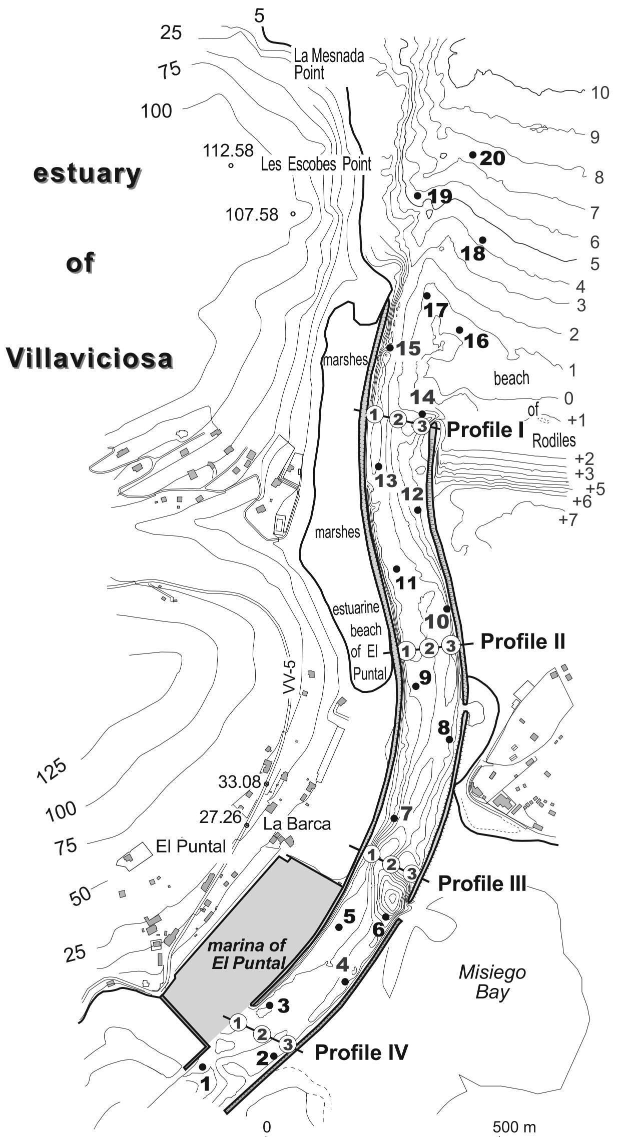

FIGURE 2. The four transverse profiles (I-IV), each one with 3 stations (1 to 3), where recorded salinities and currents (direction and velocity) were recorded from the surface to the bottom at 0.5m intervals. Bottom sand samples (1 to 20) were dredged in the channeled area and the shallow outer area. In addition, the bathymetry was recorded by monohaz.

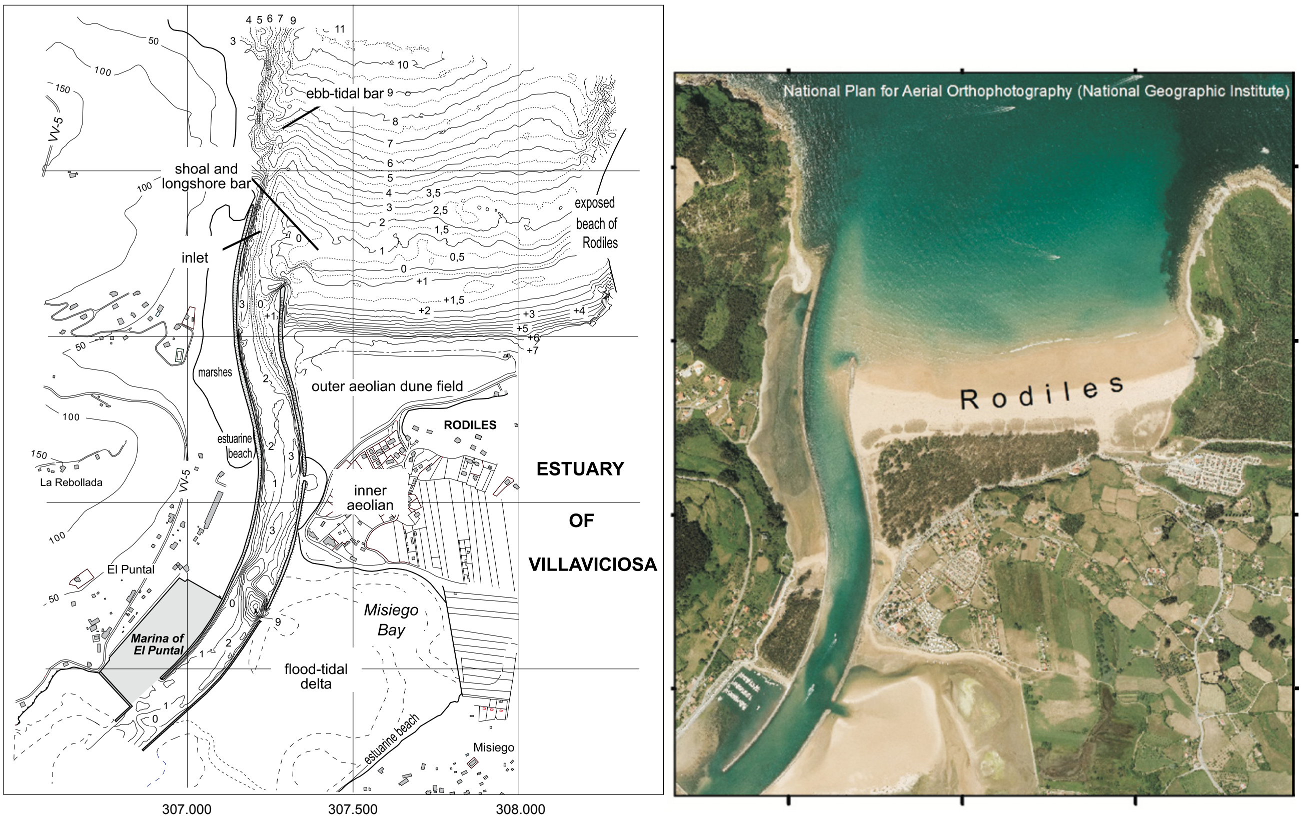

FIGURE 3. Simplified topo-bathymetric map of the main channel estuary and backshore, foreshore and offshore zones including the inner and outer inlets. Other morphosedimentary units, without avaiable topographic information, as the outer and inner aeolian dune fields, and Misiego Bay are included.

it primarily scours the low-tide terrace, which extends a few hundred meters offshore (Flor-Blanco and Flor, 2009). The low-tide terrace is strongly affected by human activity. This inlet can be classified according to Hayes (1975) as estuaries form in barrier islands dominates by waves.

Submerged bottoms flatten slightly outside, with bathymetric curves arching and generating a broad shoal linked to the low-tide terrace that stretches to the north, sometimes emerging partially during spring tides. The outer eastern channel is limited by this shoal, narrowing in the seaward direction, generated by the sand transport from the beach to the west. This constitutes the submerged part of an ebb tidal delta that is a stable sand body. Consequently, the outer inlet is located on the western side, where bottoms are relative deep (3m). To the north, there is a poorly developed mouth bar (ebb tidal delta) which represents one of the navigation problems. This bar is situated between 6 and 7m deep, being well represented in some aerial photos (Fig 3).

This complex inlet-beach system has the same position and morphology from the first historical photographs and is only modified during flood discharges, when the inlet can become eroded and deepened.

Along the channel, whose width is 80–90m in the outer area, with a maximum bottom at 3m, and then shallowing and widening (125m) upstream of the marina, the lateral bars emerge during low spring tides. A deep scour reaches depths of 9m; this occurs where the Misiego Bay drains a great volume of water and connects with the flood-tidal delta ramp that intrudes into the Misiego Bay through the opening in the right jetty.

Dynamics in the lower estuary

In the outer mouth, where there is a broad sand shoal and an ebb tide bar, the sand is removed and deposited preferentially on the western side due to the beach drift, and the velocity of the ebb current decreases outflowing along the outer inlet in the western jetty.

Along the channelised mouth (Profile I, Fig. 4), flow and ebb waters show a sinuous trajectory by adapting to the bed channel and ebb bars (emerging during low tides). The mixing of waters is weakly stratified: fresher in the east because of the Coriolis effect in the outer section and quickly changing to a vertical distribution in the inner sections. Locally, marine waters penetrate upstream during

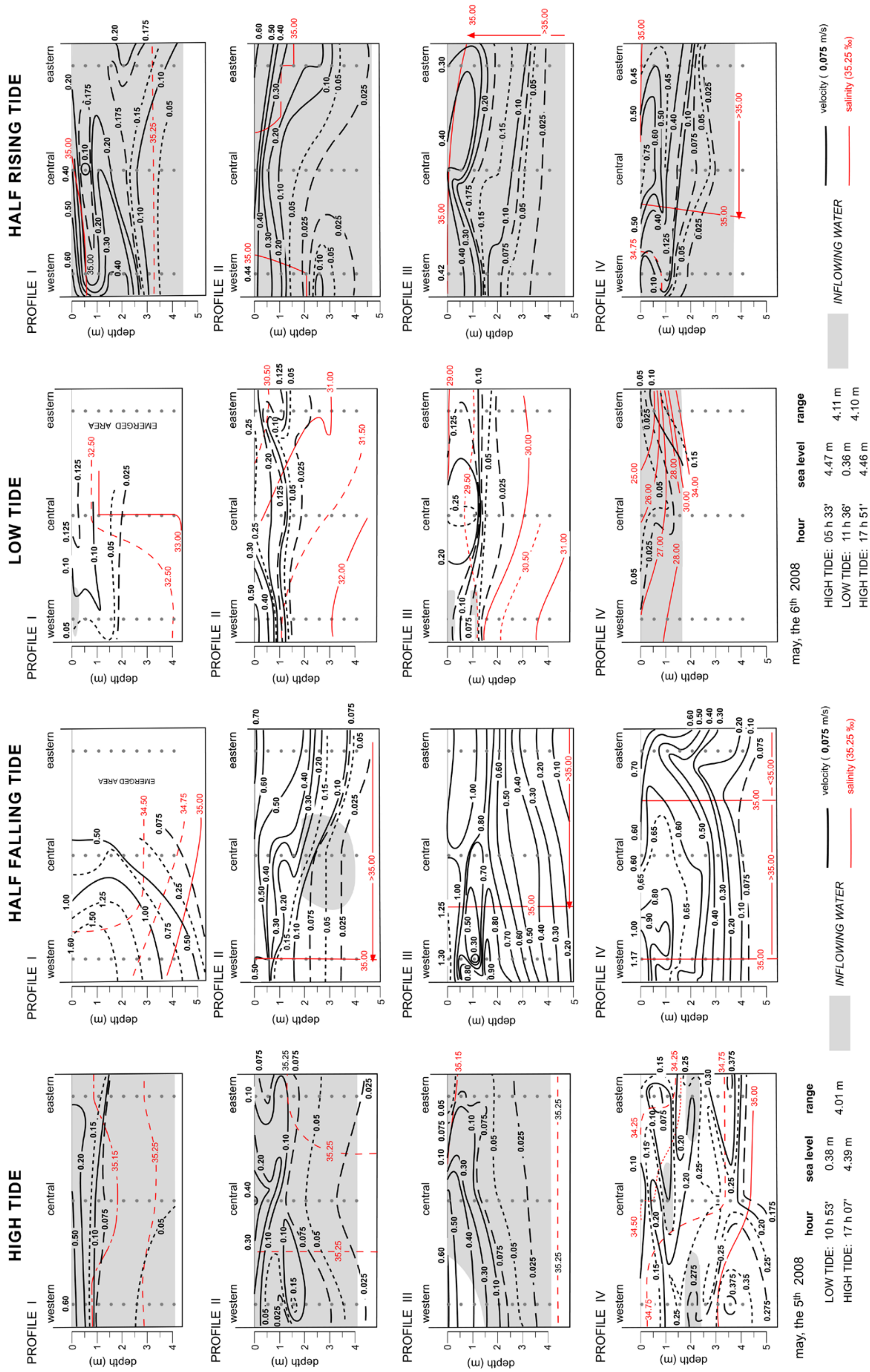

FIGURE 4. Salinities (‰) in red and velocities (m/s) along a tide cycle in the water column. Salt water intrusions are represented in grey (modified of Flor *et al.*, 2013).

the high tides as irregular fingers (Fig. 4, Profile IV), but they are not necessarily salty. During a half-falling tide, a bubble of bottom salt water penetrates upward in the central area (Fig. 4, Profile II). Moreover, during low tide, small fingers of mixed salt water enter along the western side, marking the beginning of the next tide (Fig. 4, Profile I). Ebb currents are salty in inner profiles and weakly stratified in the mouth (Profile I), decreasing the salinity during the low tide and better stratified but isohalines are oblique. Saline stratified waters intrude during the half rising reaching a quick homogeneity upstream.

The strongest current velocities (more than 0.5m/s) occur during half falling near the output of Misiego Bay (Profile III) and during rising tide in the western side of the channel, but upstream they gradually dissipate. From low tide to half rising tide, bottom salt water intrudes at a rate of 0.6m/s on the western side and 0.5m/s in the central area of the channel. During the half-falling tide, low tide ebb currents are the strongest (1.6m/s) on the western side and move persistently through the inlet toward the outer inlet. This extruding process dissipates toward the mouth bar. It decreases to the east (0.55m/s) and deviates to the NE due to the Coriolis effect in the shoal. During low tide, the flow currents are weak and occupy the bed channel, locally they can be slower than 0.5m/s (Fig. 4).

Sedimentary characteristics

Sedimentary trends

Sediments analyzed have been mapped based on main channel and bars, grain-size distributions (Gao and Collins, 1992; FitzGerald *et al*., 2000b) and drawing patterns (Cooper, 1994). The contour maps of granulometric parameters (Fig. 5) establish the sedimentary transport patterns (Van Lancker *et al*., 2004; De Falco *et al*., 2003) in the outer part of the estuary.

The textural isolines are distributed according to the bathymetries along the channelled segment: bed and bars. Sands of the bed channel are coarser (1.50–1.75ϕ) and have a higher carbonate percentage, whereas the ones of the associated lateral bars are finer (2.0ϕ) and have a lower carbonate percentage, but their sorting is better (Table 3). In the outer area, the isolines are convex to the E, showing adaptation to the shoal structure. Here, the mean size and

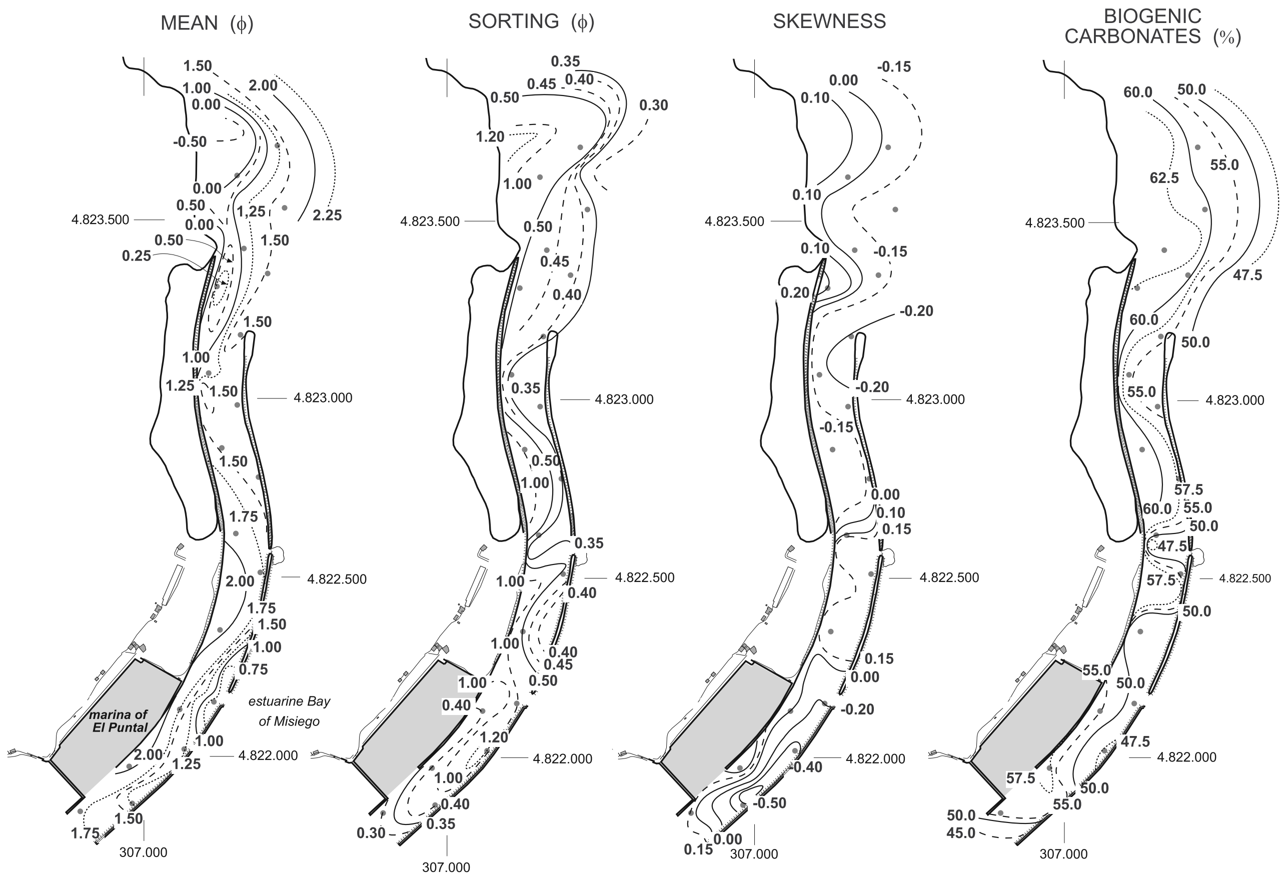

FIGURE 5. Contour maps of mean size, sorting in phi units, skewness, carbonate percent.

the carbonate percentage decrease to the E, but sorting increases as the distance from the more energetic outer inlet becomes greater. However, the lower estuary consists of sands with mean sizes varying between -0.5ф (1.41mm) and 2.0ф (0.25mm), which are classified as medium sand (Table 3). Curves are negative on the beach and become positive (a tail of finer grains) toward the inlet. Sands are very well sorted in the bars (0.35 to 0.50ф) and shoal, and sorting becomes worse in the bed channel (a more energetic area).

The most negative values of skewness are found in the main channel in front of the mouth of the marina and in the inner inlet (Fig. 5). Positive values are found in the lateral bars and in the outer inlet. Carbonates are distributed according to the mean size, as previously described, varying between 45.0% and 62.5% (Table 3).

Sand infill

In the studied area, considering the thickness between the bottom and the rocky ground, the thicknesses of the mobile sand sediments are heterogeneous, with small irregular depocenters. They are greater than 5m on the eastern side of the outer inlet due to the longshore sediment transport from the exposed beach to the western side, where the free jetty blocks an appreciable amount of sand. Other thick bottoms develop on lateral bars along the channelised main channel. The free western jetty is eroded by incoming storm waves, and some rectangular blocks occupy the left side of the outer inlet. Thus, rocky outcrops (dark blue) along both sides of the main channel and inlet (Fig. 6) with thin thickness of sand represent the blocks that have collapsed during the last 50 years.

Downcurrent, the thicknesses are relatively small in the main channel where the right jetty is connected to Misiego Bay. The water output of that bay is deviated seaward from

TABLE 3. Statistical range (Centile) and relation (Mean, Sorting and Skewness) granulometric parameters in phi and mm units, based on Folk and Ward (1957), and biogenic carbonate content

	Centile		Mean		Sorting	Skewness	Carbonates
	phi	mm	phi	mm	phi		%
ESTUARINE MOUTH							
Inlet (n=12)	-0.79	1.73	1.56	0.34	0.58	-0.04	54.16
Tidal bars (n=4)	0.29	1.22	1.67	0.31	0.41	-0.005	54.40
EXPOSED BEACH							
Emerged beach							
Beach face (n=2)	0.65	0.63	1.30	0.40	0.31	0.13	37.50
Low-tide terrace (n=2)	0.89	0.54	1.58	0.33	0.30	0.11	51.20
Submerged beach							
Very shallow (n=3)	0.20	0.87	1.84	0.28	0.58	0.09	61.00
Shallow (n=3)	0.58	0.67	2.00	0.25	0.58	0.11	53.06
Shallow-deep (n=2)	0.63	0.64	2.26	0.20	0.68	-0.14	57.50
Deep (n=2)	0.38	0.76	2.74	0.15	0.65	-0.07	39.90
MOUTH BAR							
Right arm (n=2)	-0.14	0.10	1.35	0.39	0.45	-0.15	56.10
Outer bar (n=3)	-0.26	0.19	1.06	0.48	0.64	-0.06	62.00

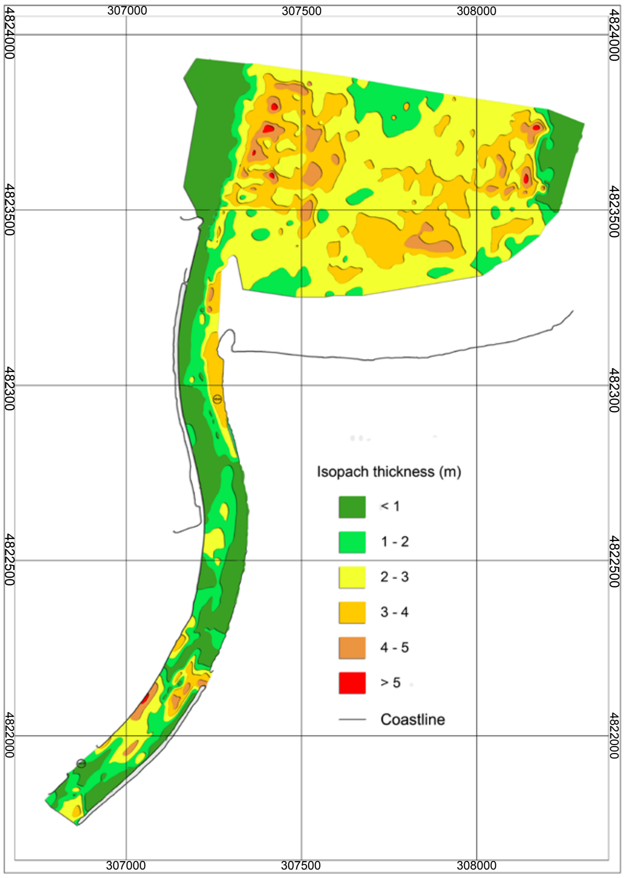

FIGURE 6. Map of isopaches at 1m intervals.

its mouth toward the opposing margin. General outflow is concentrated, and along the left margin, inflow currents are strong (Fig. 6), and there is low sedimentation in both sections of the channel.

Historical evolution and environmental management

Some projects in the estuary in the early twentieth century sought mainly to transport coal by ship to overseas from Villaviciosa, located 8km from the mouth. Previous modifications until 1925 included the channelisation of the lower main channel and inlet and the prolongation of the eastern jetty, approximately 600m seaward. Additionally, a 500m dock in the west margin and a new marina (El Puntal) were built.

The historical perspective reveals that the more important changes in the lower estuary (Fig. 7) occurred with the migration of the former inlet to the N by the construction of jetties in 1926, promoting a northward progadation of Rodiles beach and the formation of a new broad aeolian dune field (Flor-Blanco *et al.*, 2015). Moreover, Misiego Bay became gradually filled, forming a large sandy flood tidal-delta (Fig. 7 and 8).

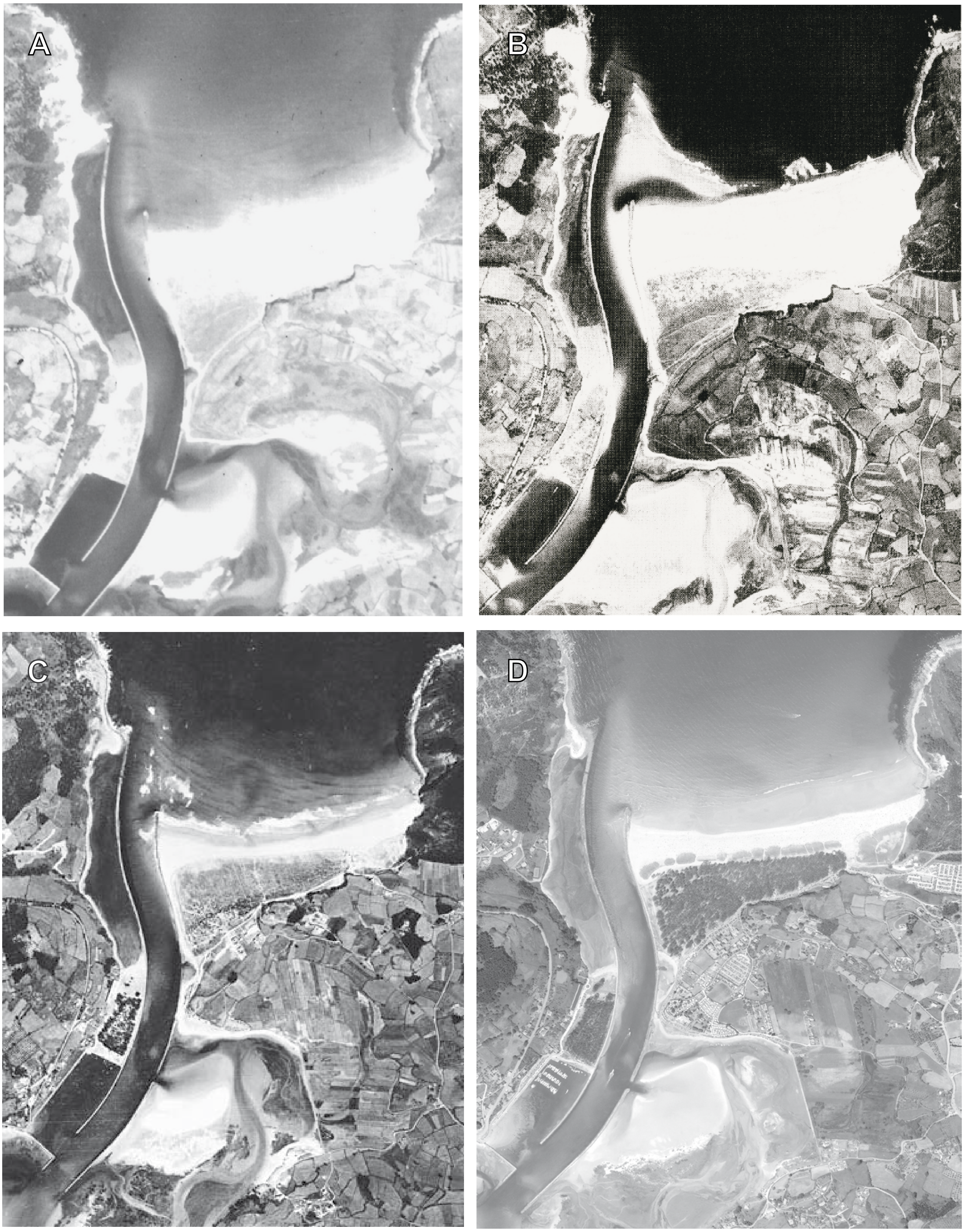

FIGURE 7. Aerial photographs of 1945A, 1956B, 1970C, 2007D showing the natural changes, specially at the estuarine beach of El Puntal Port and in the beach and aeolian dune limit of Rodiles.

In the second half of the twentieth century, several maintenance dredging were made in the marina and channel to facilitate navigation. Furthermore, in the old inner dune field of Rodiles, eucalyptus were planted and this area was progressively visited by beach users primarily during the summer periods (Fig. 7D).

In terms of natural changes after the jetties construction, the marina has been filled gradually, becoming a confined estuarine beach from 1970 to 2013. The main channel has been maintained since 1945 with the same characteristics, including the situation of the bed and its associated lateral bars.

The great shoal, situated in the external mouth bar, remained relatively unchanged until 2008 (Fig. 7), and the last field controls allowed it to extend even during 2013. This structure usually appears in many confined mouths, whether natural or man-modified, hence a continuous maintenance is needed and dredged sands have not to be transported out the system. The dredged dumping is made at less than a mile in front of Rodiles beach. Subsequently there is no sediment loss in the system and no erosion processes occurred. However, prior to dredging, the western margin of the jetty in the outer inlet, must be well restored and the stone quarry blocks should be removed to allow for safe and fast operations to maintain the mouth morphology. During dredging and after, the greatest impact is on the outer inlet and distal ebb-tide together with the strong river flood action.

Subsequently, the natural shapes of these units will be recovered gradually. Dredged sands belong to the Class 1 sediment clean material category (not contaminated) on the basis of their physical and chemical characteristics (Scortino, 2010), and have similar texture and display high remobilisation. It is suggested that sands be dumped in the submerged barrier-exposed beach at depths of less than 10m, making it more likely that sand will be recycled in the short-term (less than a decade from the dredging event). Both sand bottoms are compatible, though the average size is greater in the outer inlet, the mineralogies are similar, including the bioclastic compositions. Benthic macro-invertebrates can adapt quickly when sands bury them in few tens of centimetres (Taupp and Wetzel, 2013).

Dynamic and morpho-sedimentary behavior model

This section summarises all current data and some already published in an earlier work (Flor *et al.*, 1996). This gives the best possible understanding of the dynamic behaviour, and the distribution and geometries of sedimentary units, bearing in mind that the processes are not simultaneous. The aim is simply to have an instantaneous picture that may allow us to predict future responses to any intervention with a reasonable degree of confidence.

It is assumed that the study of morphodynamics and sedimentary evolution of estuaries is difficult (Knight and FitzGerald, 2005). Human activities induce changes in several ways, and we need to know when the impacts of an intervention can be minimised by charting morphosedimentary changes (Lesourd *et al.*, 2001). The main morphosedimentary components were summarised by Dalrymple *et al.* (1992) and partially described by Tessier (2012), who studied a wave-built coastal barrier scoured by a tidal inlet. The inner sheltered area is characterised by relatively fine-grained deposits in a central basin bay. It can be assumed that dynamics are controlled by the interactions of ebb-tide currents and, to a lesser extent, by flood entrances, although mid-term intruding sands are detected on the western side of the bay. When prevailing NW and N waves, sediment supply is provided by a persistent east-to-west longshore drift current moving from the exposed beach (Fig. 8).

The main habitats include the exposed cliff/abrasion platform, the offshore beach and the estuary, but the two latter-mentioned are less important because they are buried during the transgressive infill (Flor *et al.*, 1998). The sediments of the tidal flats and upper estuary are siliciclastic and discharged by the river floods.

In the mouth complex, the outer inlet narrows and is scoured on the shoal that occupies the lower belt of the exposed beach because sand drifts to the western area from the beach (Fig. 8). That inlet connects to a submerged narrow mouth bar with a smooth U shape and a convex seaward or simple ebb tidal delta. Strong ebb currents can remove the inlet that builds the mouth bar, but the currents are stronger during spring low tides and river floods. In this sector are generated the most breaking waves that cause navigation problems, known as Mundaka wave (Monge-Ganuzas, *et al.*, 2008). The transport occurs E–W from the beach to a broad shoal in the western area as a prolongation of the low-tide terrace. Other residual ebb currents move toward the sand shoal but lack any apparent influence (Fig. 8).

Moreover, the channel bed exhibits a sinuous geometry, developing lateral elongated bars during the ebb tide; it is only smooth in high tides. The water drained during low tides from Misiego Bay generates a broad scour 9m deep in the central and eastern sides of the channelled segment at the jetty break (Fig 8). However in this bay the most active periods occur during the half rising tide, by activation of the flood-tidal delta (Flor *et al.* 1996).

The main dynamic in the channelised estuary occur during ebb tides, when the estuary adopts unidirectional flow typical of a fluvial model. Strong ebb currents are concentrated in the western side, generating an outer inlet that narrows to the south.

DISCUSSION

According to Dalrymple *et al.* (1992), Cantabrian estuaries, including Villaviciosa, are wave-dominated estuaries (WDE). However, following Pritchard (1967) and Fairbridge (1980) classifications, Villaviciosa estuary fits with a barrier-built and low relief estuary, L-shaped (bar-built estuary), respectively. In barrier estuaries, tidal circulation depends on the hypsometry during the tidal cycle (Boon and Byrne, 1981). A complementary study of the mechanical tidal waves during a spring tide in a river (Le Floch, 1961), reveals that it is a hyposynchronous estuary (decreasing the tide range upstream) as conditions described by Dalrymple and Choi (2007). Roy *et al.* (2001)

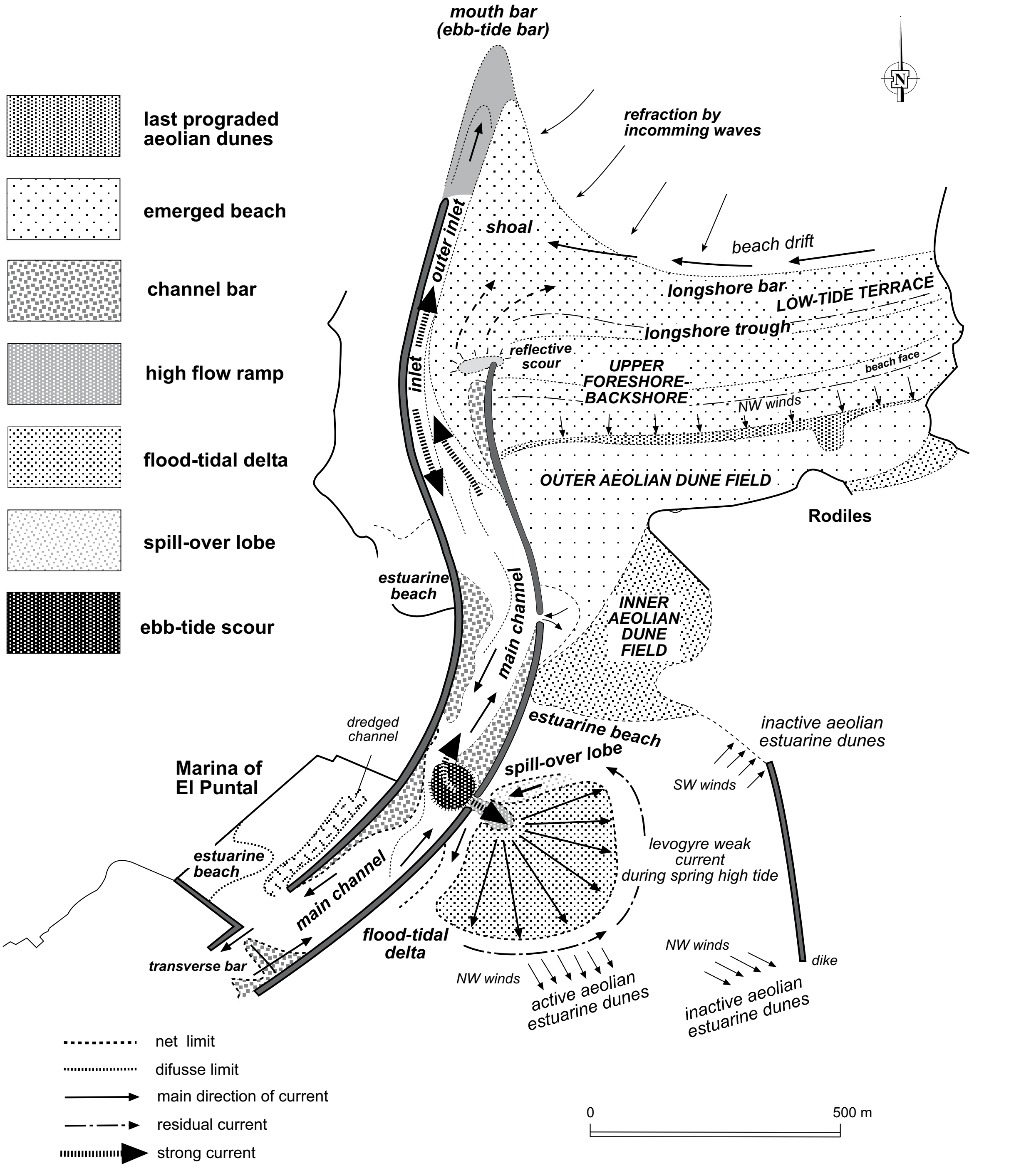

FIGURE 8. Morpho-sedimentary, dynamic model of the lower Villaviciosa estuary where ebb currents are the most important event, interact with the beach drift E–W to built the broad shoal and the outer inlet.

suggested that high-energy environments are restricted to the most seaward part of the entrance channels of barrier estuaries. Moreover, there are complex interactions between tides and waves.

The Asturian inner continental shelf is considered to be an undernourished area (Fernández-Valdés, 1997), except for the infilled old submerged valleys located in front of the mouths. Cores taken for geotechnical studies in the inner areas of Cantabrian estuaries (Alonso and Pagés, 2010) recorded sedimentary infill with a metric to decametric thickness in Villaviciosa estuary and highly variable in other estuaries (Bruschi *et al.*, 2013).

Many micro and mesotidal estuaries confined by barriers, were studied in their mouth areas, and their behaviour was found to be highly variable throw dynamic, geomorphologic and sedimentary perspectives (Cleary, 1996; FitzGerald, 1996; FitzGerald *et al.*, 2000a). When major ports were constructed, the estuaries experienced human-derived transformations: fill tidelands, dike salt marshes, jetties and dredging (Johnston, 1981; Van Rijn, 2005; Blott *et al.*, 2006; Toffolon and Crosato, 2007). These cases can be extrapolated to estuaries attached to fluvial excavated systems (Wang *et al.*, 2002), as Villaviciosa, developed in a temperate region that can be considered an incised-valley system (Zaitlin *et al.*, 1994). Another example is the Oka estuary (Basque Country) on the eastern Cantabrian coast, analogous in several ways to the Villaviciosa estuary (Flor and Flor-Blanco, 2006), especially in the outer area, where the ebb bar (Mundaka sandbar) is an ebb tidal delta (Liria *et al.*, 2009). It has been dredged and the sediments were dumped in the barrier, causing major erosion and the migration of the inlet. However, subsequently, the mouth environment recovered its natural dynamics and morphology (Monge-Ganuzas *et al.*, 2008).

The most important variables that control the sedimentary and dynamic complex around an estuarine inlet are the tidal prism, the inlet geometry, wave and tidal energy, sediment supply, spatial distribution of backbarrier channels, slope of the nearshore and engineering modification (FitzGerald *et al.*, 2000a). Evaluating these premises, the morpho-sedimentary and dynamic morphologies have maintained a state of quasi-equilibrium since 1945 (Fig. 8), as many other estuaries in the world (Cooper, 2002; Bryce *et al.*, 2003).

In addition, it must be taken into account that the sea level has risen approximately between 1.7±0.2mm/yr (García-Artola *et al.*, 2014) and 2.0mm/yr (Leorri and Cearreta, 2009) in the Cantabrian coast during the 20th century. This process and human actions have affected the erosion of the outer dune belt from 1970 to 2005 (Flor-Blanco and Flor, 2009).

Since 2001, restricting access and isolation of the enclosures promoted a progradation of sand sheets and incipient foredune with a rapid colonisation by Ammophila arenaria (Flor-Blanco *et al.*, 2015). Additionally, in south western part of Misiego Bay there is a slow sand migration, recovering the mud facies upstream.

One engineering proposal is to extend the eastern jetty by approximately 200m, but previous studies (Flor-Blanco and Flor, 2012) had demonstrated that bathymetries will become shallow after a few years, with the northward migration of the bed forms. From an environmental point of view, the impact will be negative in this protected area because it will have a greater accumulation of sands on the western margin of the beach by the littoral drift, swivelling the beach planform to the southeast and erosion of the Rodiles east southern fringe. Consequently, any changes in the mouth management may affect the beach-dune system.

Furthermore, the output of the navigation channel would lose the natural protection of the outer capes. Thus, the best solution is to maintain the dredging despite expecting a relatively rapid reposition of the sediment in the dredged area. This dredging must be restricted to the outer inlet such that the periodicity increases when sands drifted causes the bottom shallower. It is important to keep the lateral bars, although the channel bed attached to the jetty needs dredging. These lateral bars are well-stabilised and they allow the strong ebb currents to carry along the more scoured area.

It has been suggested that the dredged material should be relocated in the vicinity of the dredging site (Meyer-Nehls, 2000). Hence, bottom sands in neighbouring ports or marinas, generally dredged in shipping channels were mainly expelled to the outer shelf. Some took advantage of the dredging to nourish estuarine beaches, even generating some new beaches inside the estuary or restoring the aeolian field, thus closing a natural circuit of sand transport (Medina *et al.*, 2007) despite the trend of disposal of dredge spoil beyond the closure depth (Flor-Blanco *et al.*, 2013).

Other option is to dump the dredging on the top of the barrier to restore its confining morphology as in Oka estuary (Monge-Ganuzas *et al.*, 2013), generating a new dune field (Iriarte *et al.*, 2004). This methodology can be applied to the Villaviciosa mouth or similar estuaries and the results will be determined in the short- and medium-term.

CONCLUSIONS

Morphological, dynamic and sedimentary methodologies have been used in this paper, in addition to aerial photographs since 1945. This gives us enough information to understand the interconnected processes that occur in the lower mesotidal Villaviciosa estuary. The associated marina of El Puntal has considerable socio-economic value. It provides indirect employment and recreational facilities, which justifies the goal of extending the spot boat dock areas and troubleshooting navigation in the area.

Some solutions are proposed for this case study such as an improvement in the jetties system, which would help to control the channelization and allow the Rodiles beach-dune system keep its current morphology. To preserve safe condition for the navigation in the mouth of the estuary is recommended periodically dredging, only in the narrow inlet, and dumping the sediments not beyond the closure depth. Thus, the loss of sediment in the system would be interrupted and the dredging intervals enlarged.

This study could be exportable to similar environments and help to management policy, reducing the impact in these highly sensitive environments. The maintenance of dredgings improves certain channels access and port basins subject to high sedimentation, making possible the preservation of the estuarine habitats.

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