***Journal of Iberian Geology* 41 (3) 2015:** 315-332
http://dx.doi.org/10.5209/rev_JIGE.2015.v41.n3.50313

www.ucm.es/info/estratig/journal.htm
ISSN (print): 1698-6180. ISSN (online): 1886-7995

Journal of Iberian Geology
AN INTERNATIONAL PUBLICATION OF EARTH SCIENCES

Hydrodynamic controls of morpho-sedimentary evolution in a rock-bounded mesotidal estuary. Tina Menor (N Spain)

G. Flor-Blanco[1]*, G. Flor[1], J. A. Morales [2], L. Pando[1]

[1]Department of Geology. University of Oviedo. GeoQuo Research Group (Geomorphology and Quaternary). Campus de Llamaquique. C/ Jesús Arias de Velasco, s/n. 33005-Oviedo. Spain.
[2]Department of Geology. University of Huelva. Campus de excelencia CEI-Cambio, Avenida 3 de marzo, s/n. 21007-Huelva. Spain.

*e-mail addresses: gfb@geol.uniovi.es (G.F-B, *Corresponding author), gflor@geol.uniovi.es (G.F), jmorales@uhu.es (J.A.M), lpando@geol.uniovi.es (L.P)*

Received: 28 September 2015 / Accepted: 1 December 2015 / Available online: 20 December 2015

Abstract

The Tina Menor estuary is a highly confined incised valley with advanced sedimentary infilling. The outstanding feature of this estuary is its longitudinal zonation, which forms four segments from the outer to the inner limit: *Mouth complex*, *Bay*, *Tidal flats* and *Upper channel*. The innermost part of the Bay and the Tidal Flats (semi-reclaimed areas) are broader estuarine zones, whereas the Mouth Complex and outermost Bay are confined by narrow rocky outcrops. This paper explains the dynamics and sedimentary distribution of a highly confined and singular estuary, detailing the fluvial-tidal controls on the variations in water mixing (QF/QT). This estuary is largely of salt wedge type and the dynamics are characterised by recording currents (speed and direction) in the water column during a tidal cycle in a spring tide; this process consists of the tidal waves propagation and their dissipation upstream hypo-synchronously and the mixing of fresh and saline waters.

The morphology, dynamics and sedimentary distributions have been integrated to develop a conceptual model that demonstrates the circulation within the estuary. The sinuous geometry of the estuarine valley and the Coriolis Effect detected, play a fundamental role in determining the morphology and sedimentary distribution. Consequently, this study provides an adequate overview of this type of confined mesotidal estuary, quite common in the eastern Atlantic coast.

Keywords: estuary, mesotidal, Bay of Biscay, morpho-sedimentary processes

Resumen

El estuario de Tina Menor es un valle encajado altamente confinado y sedimentariamente en un avanzado estado de colmatación. Se caracteriza por su zonación longitudinal en cuatro segmentos bien diferenciados desde su sector más externo hasta el límite interior: *Complejo de Desembocadura*, *Bahía*, *Llanuras Mareales* y *Canal Superior*. El interior de la Bahía y las Llanuras Mareales de carácter fangoso (zonas semi-reclamadas) son las más extensas, mientras que el Complejo de Desembocadura y la parte externa de la Bahía, están estrechamente confinadas por afloramientos rocosos. Este trabajo explica la distribución dinámica y sedimentaria de un estuario singular y altamente confinado, detallando los controles fluviales-mareales en la variación de las mezclas de agua (QF/QT). Este estuario es en gran parte del tipo de cuña salina y la dinámica fue caracterizada por las medidas de corrientes (velocidad y dirección) realizadas en la columna de agua durante un ciclo mareal en marea viva; este proceso consiste en la propagación de las ondas de marea y su disipación de aguas arriba hipo-sincrónicamente y la mezcla de aguas dulces y salinas.

La morfología, dinámica y las distribuciones sedimentarias, se han integrado para desarrollar un modelo conceptual que demuestre la circulación dentro del estuario. La geometría sinuosa del valle estuarino y la detección del efecto de Coriolis, juegan un rol fundamental para determinar la distribución morfologica y sedimentaria. Consecuentemente, este estudio proporciona un visión adecuada de este tipo de estuarios mesomareales confinados, tan comunes en las costas atlánticas orientales.

Palabras clave: estuario, mesomareal, Golfo de Vizcaya, proceso morfo-sedimentario

1. Introduction

The northern coast of Spain (Bay of Biscay) is 605 km long, trending W-E and includes more than 50 estuaries that greatly vary in size and degree of sedimentary infilling (Bruschi *et al.,* 2013). All of them are characterized by an important control of the hard rock substrate (rock-bounded estuaries) and a typical morphology of wave-dominated estuaries in a partial state of infilling.

Tina Menor is one of the largest estuaries of this coast, displaying a diverse range of sedimentary sub-environments and facies, similar to other mesotidal estuaries all over the world. However, in this case, certain estuarine features typical of wave dominated estuaries, such as closure barriers or wider salt marshes, are absent.

The morphology of this estuary was previously described by Fontan (2001) and similar estuaries in the Cantabrian coast have been studied to characterize their general features and dynamics (Flor and Camblor, 1990; Flor *et al.,* 1992; Flor *et al.,* 1996; Uriarte *et al.,* 2004; Flor *et al.,* 2015). Other rock bounded estuaries have been described in the northwest of Iberian Península (Evans and Prego, 2003; Naughton *et al.,* 2007), France (e.g. Menier, 2006; Chaumillon et al 2008; Sorrel *et al.,* 2010; Tessier, 2012), United Kingdom and Ireland (Burningham and Cooper, 2004; Cooper, 2006) and South Africa (Cooper, 2001).

This paper aims to characterize the propagation upstream (tidal and saline waves) until its dissipation in the estuarine head. The fieldwork was designed to develop a scheme of currents throughout the water column along a tidal cycle. This scheme is linked with the sedimentary patterns of surficial deposits, paying great emphasis on the distribution of sand and gravel fractions, so as the geomorphological zonation of morpho-sedimentary and dynamic units. In this paper, the aforementioned themes are studied, enabling a better understanding of the Tina Menor estuary and including the synthesis of the dynamic and sedimentary processes through the elaboration of a simplified model. This conceptual model accounts for the marine and continental influences throughout the estuary. This link between tidal dynamics, fluvial input and sediment distribution could be a good example to compare with other similar estuaries.

2. Location and General Setting

The study area is located on the western coast of Cantabria in Spain (Fig. 1) within the central-eastern area of the Bay of Biscay (NW Iberian Peninsula). This stretch of coast has steep cliffs with slopes up to 65 m high, that are interrupted by Tina Menor and Tina Mayor (which is located 3.45 km W) estuaries, both with narrow rocky mouths. The littoral belt has been sculpted in Carboniferous limestone, but to the south, a coastal range has formed in a quartzitic formation (Ordovician Armorican Quartzite-Barrios Formation). Tina Menor estuary is confined by these Palaeozoic formations, culminating in flattened surfaces containing two erosive continental plains belonging to the erosional surfaces (*rasas),* II (previous coastal altitude of 220 m) and III (185 m), according to Flor and Flor-Blanco (2014). The estuary is represented by a fluvial valley that is almost completely infilled by sediments. Main surficial sediments are siliceous sands and muds, whereas the pebbles and gravels constitute a significant sedimentary fraction of the beaches in the inner estuary. Bedload transport of sand along the estuary is generally controlled by the local dominance of ebb or flood currents (Dronkers, 1986). The tidal action is normally reflected in the abundant subaerial bedforms.

The inner estuarine limit is near 4.80 km from the mouth, considering the inner limit of the tide propagation during spring high tides (with south low fluvial runoff). The system is affected by mesotidal semidiurnal tides and drained by the Nansa River, which supplies quartzite and sandstone gravel

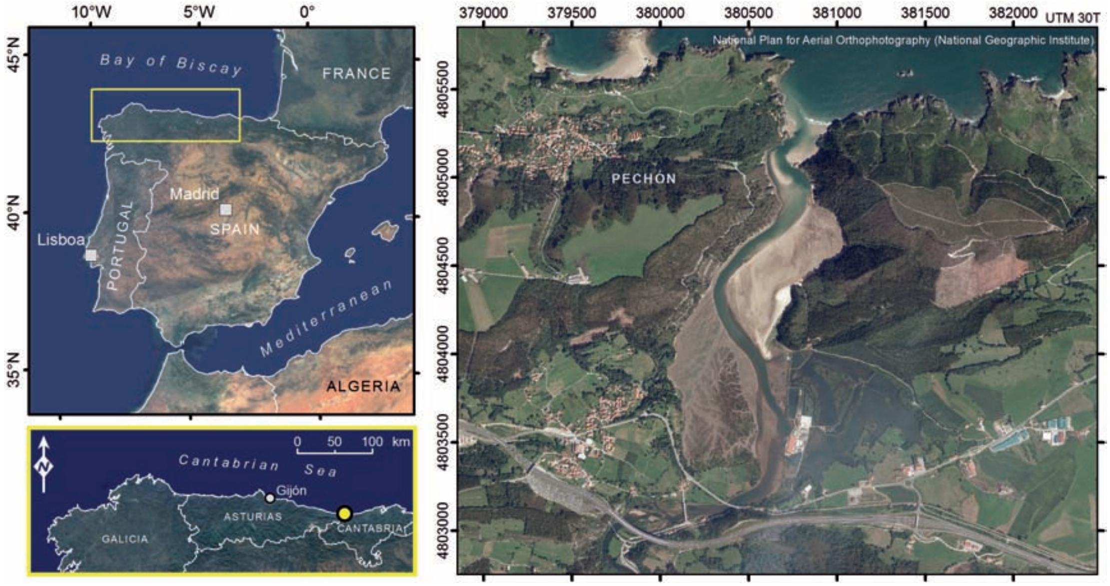


Fig. 1.- Location of Tina Menor estuary (Northwestern Spain)

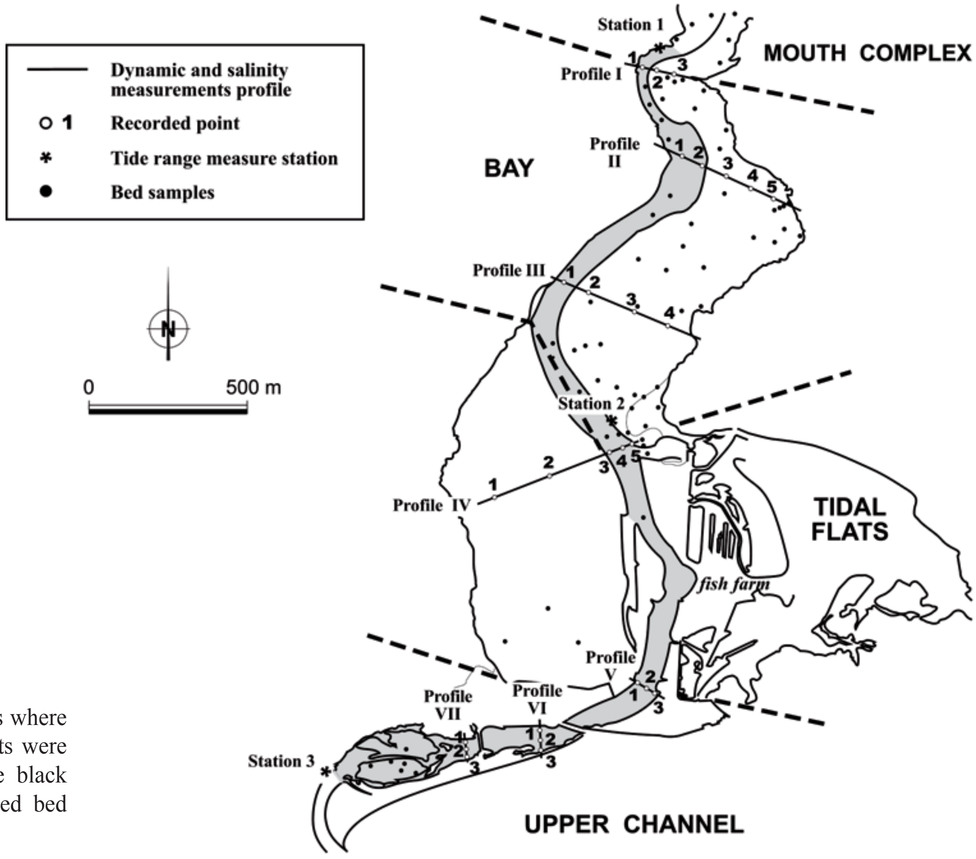


Fig. 2.- Position of profiles and stations where tidal range, salinity and flow currents were recorded in the water column. The black points mark the position of collected bed samples.

fractions and also provides siliciclastic sands and suspended mud particles. Similarly to other Cantabrian estuaries (Flor *et al.*, 1998), the scarce bioclastic sand content is attributed to a rework of relict sediments from the coastal submerged prism and others originate from the inner part of this estuary (Pascual *et al.*, 2009). The gravels are normally deposited in the bay head delta, whereas sand fractions occupy central and outer estuarine areas (*Bay* and *Mouth complex* zones) and the muds are stabilised in the *Tidal flats*, as well as in the broad reclaimed eastern area.

The most defining feature of this estuary is a confined mouth by narrow rocky outcrops. The closure system also develops a small sand barrier that is submerged during high tides. A particularity of this estuary is the presence of a broad inner barrier, permanently emerged and anchored on the eastern side. This barrier displays a relatively exposed estuarine beach, with an aeolian field. The geometry of the valley slopes in the outer estuarine section exerts a morphological control over the location of the main channel, sand flats and inner barrier, inducing a dynamic and a singular sedimentary distribution in the estuarine bay. Similarly to the situation in New England (USA), the structural controls strongly affect the geometry of the drainage systems, as well as the position and morphology of the estuary mouth (Fitzgerald, 2000). These geological controls are important during the evolution of estuarine systems in the accommodation space for inter- and supratidal sedimentary bodies as in other atlantic estuaries (Burningham and Cooper, 2004; Burningham, 2008).

3. Material and Methods

The representative morpho-sedimentary and dynamic units were mapped using a 1:5,000 (2010) scale and the ortophotographs from 2007 and 2010, in addition to 1:5,000 topographic charts from 2001 (Cartographic Service of Cantabria) and a 1:5,000 Cantabrian DEM (2010), with a resolution of 5 m.

Data concerning fluvial discharges from the Nansa River were obtained from the *Comisaría de Aguas del Norte de España* (Ministerio de Fomento) and a hydroelectric company that operates a series of dams upstream (*Saltos del Nansa)*. The data were used to calculate the volume of freshwater that is introduced into the estuary during the low regime and flood runoff stages of a tidal cycle. Furthermore, the saltwater inflow volumes during the neap and spring tides (1.0 and 4.5 m range and maximum range, respectively) were calculated using profile measurements throughout the estuary for a complete tidal cycle (Fig. 2). Based in Pritchard (1955) and Cameron and Pritchard (1963), three end possibilities for the mixed waters were estimated after applying the modified flow ratio limit developed by Simmons (1955). In this paper, the numerical limits of the flow ratio are modified: 0.01-0.10 (vertically homogeneous), 0.10-1.0 (partially mixed) and >1.0 (highly stratified).

The tidal levels were recorded using direct measurements obtained with a tide staff divided vertically into centimetre intervals. Four stations in the main channel were selected from the mouth to the inner estuary, and the data were acquired every 10 minutes throughout a nearly full tidal cycle during a spring tide with medium-high fluvial runoff. The saline and mechanical tide propagation measurements were recorded during low fluvial discharge and spring tides (Fig. 2). In addition, these time-height curves were compared to theoretical tides in open sea (station one) and deduced from the tide table (2011 forecast data) for Gijón harbour (located approximately 100 km to the W).

To interpret the sedimentary dynamics along a spring tidal cycle, the circulation scheme was obtained by recording the current velocity and direction, as well as the saline distributions through the entire water column at 0.5 m depth intervals up to a maximum depth of 4.50 m. A boat equipped with two different current meters, General Oceanic, Inc. Model 2031H and Global Water 800-876-1172 Model FP101 and a handheld multiparameter instrument (Ysi Mod556 MPS) were used along seven transverse profiles (Fig. 2), separated by 300-500 m relative to the axis of the estuarine channel. Three recording stations were established in each profile with one on both sides and one in the centre, were numbered 1, 2, and 3 in the western, central and eastern parts of the main channel, respectively. If a section was wider (profiles II, III, and IV), additional points were taken into account (1 to 5).

Wave data were also analised to have an approach to the wave influence on the outer part of the estuary. These data were obtained from the WANA point 1062074 (*Puertos del Estado)*, for the period 2000 to 2012.

In addition, several representative surface samples (71) were taken on the surface or in submerged areas with a Petersen dredge mounted on a boat. The samples were analised to obtain the grain-size distribution (textural parameters) and biogenic carbonate content to correlate with the sediment transport. The textural parameters were obtained using the Folk and Ward (1957) method and the software GRADISTAT (Blott and Pye, 2001).

To complete the sedimentological information, the intertidal bedforms were directly measured during low tide periods. Subtidal bedforms were also measured using a monobeam echo-sound with a frequency of 210 kHz.

All data and information were subsequently processed in a GIS (ArcGIS, ESRI Inc.), and the maps and figures were generated using that software and other graphic editing programs.

4. Results

4.1. Environments: Morphology and Sedimentology

The estuary is divided longitudinally into the following four areas (Flor, 1995), distributed from the mouth to the inner estuarine limit (Fig. 1): *Mouth complex*, *Bay*, *Tidal flats* and *Upper channel*. This distribution is also found in most of the Cantabrian and Galician estuaries (Flor-Blanco and Flor, 2012) and can be considered as the typical zonation of a mesotidal estuary in a partial state of infilling according with the criteria of Roy (1984). Each zone is constituted by several environments or morpho-sedimentary units (Fig. 3).

Mouth complex (marine estuary)

The rocky outcrops confine the mouth to a minimum of 75 m wide and 400 m long area and only allow the formation of a small sand barrier. This barrier is poorly developed and is anchored on the eastern side. The barrier only consists of an exposed sand beach oriented along a NE-SW direction, which has a narrow and relatively steep talus in the upper belt and, at low tide, directly connects with the inner flood ramp (Figs. 4A and B). This sediment consist of well-sorted fine sand with 2.45 phi mean (Wentworth, 1922; Folk and Ward, 1955). The percentage of carbonate is higher in the channel than at the beach (Table 1). On the surface of the exposed beach symmetrical straight-crested (2D) ripples are developed (Table 2).

According with the eastern position of the barrier, the inlet is directly connected to the main channel on the western side of the mouth. In the middle inlet, an oval depression is scoured about 7 m under low spring tidal level. During normal ebb currents most of the tidal energy is dissipated across the closure. In exceptional events, during high discharge events in the Nansa River, the inlet migrates to the eastern side and remains in that position for several months.

The inner sector forms an arc convex toward the W due to an adaptation of the confining barrier (Fig. 3). The sand banks located outside the mouth are episodically reworked (and even disrupted) during extreme fluvial discharge events (González *et al.,* 2004; Dias *et al.,* 2004), forming a sediment dispersal river-plume that is pushed eastward by the drift current.

Bay (outer central basin)

Two areas can be differentiated: the northern area follows a NW-SE direction and contains larger bed structures, specifically flood tidal deltas and the spill-over lobes (Figs. 3 and 4A); the southern section is much more extensive, containing various morpho-sedimentary and dynamic units (main estuarine channel, sand flats, tidal creeks and estuarine beach) (Figs. 3 and 4E). Across the entire *Bay*, the sediment is well-sorted fine sand, with carbonate contents between 5.60 and 13.75% (Table 1), except in the estuarine beach (eastern part), which is composed of gravels and pebbles coming directly from the cliff.

In the central and eastern belt of the outer area of the *Bay* (Fig. 3), a large tidal flood-delta is generated in a western position, whereas another minor ebb spill-over lobe downstream-oriented is found on the opposite side. This flood-tidal delta is elongated and has acquired an asymmetric geometry as an incipient barrier. On the western side, both flood and ebb-oriented sand waves (medium 2D dunes) are present (Table 2).

Upstream of the rocky confined area, the western margin of the main channel continues to be covered by quartzitic coarse

	Mean		Sorting	Carbonates
	ϕ	mm	ϕ	%
MOUTH COMPLEX				
Inlet (n=3)	2.14	0.22	0.47	14.40
Exposed beach				
Upper foreshore (n=1)	2.47	0.18	0.34	6.00
Low-tide terrace (n=2)	2.44	0.18	0.35	6.10
BAY				
Main channel				
Outer main channel (n=3)	2.2	0.22	0.47	6.53
Inner main channel (n=6)	2.12	0.23	0.48	10.1
Flood-tidal deltas & splill-over lobes				
Outer flood-tidal deltas & splill-over lobes (n=4)	2.3	0.2	0.42	13.75
Inner splill-over lobe (n=2)	2.25	0.21	0.46	5.6
Estuarine beaches				
Outer beach (n=1)	1.98	0.25	0.4	6.2
Inner beaches (n=4)	2.56	0.17	0.38	7.3
Gravel beach (n=5)	-4.55	23.42	0.37	-
Sand flats				
Proximal sand flat (n=9)	2.38	0.19	0.43	10.42
Distal sand flat (n=11)	2.54	0.17	0.35	11.94
Estuarine aeolian dunes				
Active dunes (n=1)	2.64	0.16	0.29	9
Vegetated dunes (n=4)	2.59	0.17	0.34	13.05
TIDAL FLATS				
Main channel (n=3)	1.35	0.39	0.61	10.26
Mud flats (n=3)	4.66	0.04	1.35	18.46
UPPER CHANNEL				
Main channel (n=2)	-0.19	1.14	1.61	12.4
Welded gravel bars (n=7)	-0.86	1.82	1	-

Table 1. Averaged granulometric parameters of the estuarine morpho-sedimentary units.

SECTOR	ENVIRONMENT	BEDFORMS	DIMENSIONS (m)
Mouth complex	Main channel	Not observed	
	Exposed beach	Ripples (2D)	L: 0.02-0.03 H: 0.01
Bay	Main channel	Medium dunes (2D-3D)	L: 3.0-4.5 H: 0.5
	Outer flood tidal deltas	Medium dunes (3D)	L: 3.0-4.5 H: 1.0
	Spill-over lobes	Medium dunes (3D), superimposed ripples (2D-3D)	L: 3.0-4.5 H: 1.0 L: 0.03-0.04 H: 0.1-0.3
	Inner flood tidal deltas	Medium dunes (2D)	L: 4.5-9.0 H: 0.5-1.5
	Proximal sandy tidal flats	Medium dunes (2D-3D) and scours	L: 2.0-4.0 H: 0.5-1.0
	Distal sandy tidal flats	Ripples (2D)	L: 0.02-0.05 H: 0.1-0.2
Tidal flats	Main channel	Not observed	
	Muddy tidal flats	Lower plane bed	
Upper channel	Main channel	Not observed	
	Bars	Plane bed	
	Fluvio-tidal flats	Lower plane bed	

Table 2. Shape and dimensions of bedforms described on the different estuarine morpho-sedimentary units.

talus debris. On isolated occasions, this phenomenon itself manifests as a broad asymmetric spill-over lobe with numerous superimposed bedforms (Table 2). However, it has developed an internal wide flood-tidal delta where around the flood ramp flood-oriented megaripple fields (medium 3D dunes) are developed, as well as numerous superimposed linguoid, lunate and straight ripples (Table 2; Fig. 4C, E).

The sand flats are the broader unit in the *Bay* and can be subdivided into two belts relative to the main channel: proximal and distal flats (Fig. 3). The proximal flats, which are a more energetic environment, host the best represented bedforms as medium dunes 2D and 3D and scours (Table 2). The distal flats, slightly depressed, allow for the outgoing ebb to flow along this margin (Fig. 4B), normally, these distal flats displays an extensive plane bed. Moreover, estuarine beaches are present only on the inner eastern side and are mostly composed of very fine sand, as well as gravel reworked directly from the cliffs.

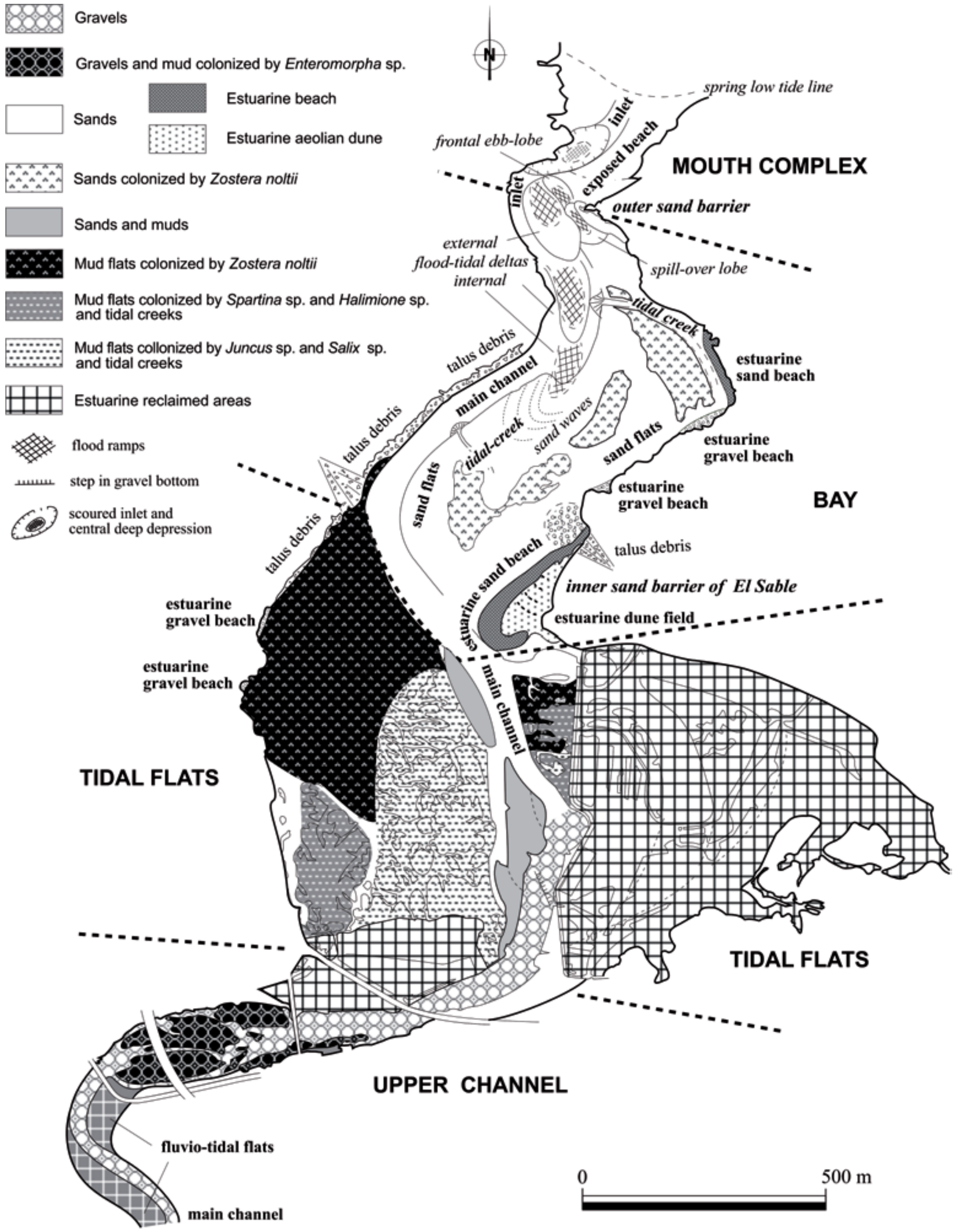


Fig. 3.- Geomorphological zonation and main morpho-sedimentary and dynamic units, including the most important large-scale sedimentary structures.

One of the peculiarities of the estuary is the presence of the estuarine beach (El Sable barrier) (Figs. 3 and 4D), formed by sand sheets and some foredunes with a smoothed crest (NW-SE). The foredunes are oblique to the water line and spaced between 15 and 20 m, following a northwestward progradation. In the southern area of the barrier, a small spit develops with active embryonic dunes. Until 2010's, this spit was perpendicular to the estuary axis, but at present, both are nearly parallel. The logical position of sandy barriers (spits) should be in the mouth, however, this barrier is located in the eastern margin of the inner bay, because the typical position of these type of spits (mouth) is very narrow whereas the innermost zone of the Bay is wider, allowing the development of the barrier.

Tidal flats (inner central basin)

This area is the broadest estuarine zone, containing sedimentary fine sizes (Table 1). The Tidal flats extend along both sides of the main channel, but only those in the western area are active (left bank of the main channel) with a surface area of 22.53 ha. The other area is wider (47.54 ha), including an old abandoned main channel and other tidal flats; the region has been partially reclaimed, but is dynamically isolated (Fig. 3). The morpho-sedimentary units are: main channel, mud flats, marshes, tidal creeks and tidal ponds.

The main estuarine channel switches to the eastern margin in this zone from the Bay, leaving the most active units on the western side. Its dominant sediment is composed by well

Fig. 4.- A) *Mouth complex* with the flow and ebb spill-over lobes in Tina Menor estuary during a low spring tide. B) 3D block-diagram (DEM and 2010 orthophotograph of Gob. Cantabria and IGN-CNIG). Mouth confinement and *Bay* with sandy flats with tidal channels and a part of *Mud flats*. C) Sand waves overlapped to inner spill-over lobe. D) View of El Sable barrier and inner *Bay*. E) Oblique aerial view from the southwest to the north, including the *Mouth complex*, *Bay* and a small portion of the *Tidal flats*. F) *Mud flats* collonized by *Spartina*, *Halimione* and the tidal creeks.

sorted medium sand with high carbonate contents up to 10%. (Table 1), the bedforms in this environment could not be observed because their subtidal character.

The muddy tidal flats occupy the largest area. However, the mud flats are composed of moderately sorted coarse silt with the highest carbonate contents (near 19%), extending both sides of the main and tidal creeks while occupying narrow and irregular belts. Essentially, three types of vegetated flats can be distinguished relative to the dominant species (Loriente, 1987), and their increases in height have been mapped: the mud flats in the northern area are colonised by *Zostera noltii*, adopting a subrectangular surface along N-S direction; *Spartina maritima* and *Halimione portulacoides* marshes (Figs. 3 and 4F) are restricted to the SW edge with a rectangular surface measuring 240 m long (N-S direction) and 170 m wide; and the upper marshes have been colonised by *Juncus* sp. and *Salix* sp.

Upper channel (fluvial estuary)

The main channel is the most energetic unit represented in the inner estuary, joining the Nansa River 2,225 m upstream. This channel is relatively sinuous, but there are long straight segments in the inner section. Several welded braided bars and minor channels were developed in this sector. These bars are constituted of a base of poorly sorted gravels (composed of quartzite and sandstone rounded pebbles) covered with siliciclastic coarse-medium sand and muddy layers (Table 1). The bars are partially colonised by *Enteromorpha* sp. Upstream, the beds are characterised by relatively flat beds and longitudinal gravel bars, however, sometimes have ebb spill-over geometries (Fig. 3) while overstepping their own sediments. In some places, the channel flows directly over the rocky substrate.

The fluvio-tidal flats are narrow surfaces in their outer portion, while remaining broader in the inner estuary (eastern margin). The flats are only active during spring high tides and flood river discharges. Some old longitudinal bars, which most likely originated as laterally migrating point-bars, and a river-tidal creek, are now part of the flats (Fig. 3). Major river floods can deposit gravel and sand sheets on the inactive plains.

4.2. Hydrodynamics

Incoming waves

In the Cantabrian Sea, waves from the fourth quadrant dominate; the largest originate from N60^{0}W-N20^{0}W. Waves from N20^{0}W to N15^{0}E are also important during under anticyclonic conditions. In this coastal region, most swell or wind waves come from the NW (25%), with 77% emanating from 270-360ºN (González *et al.,* 2004). The significant wave height is below 2.0 m (39.9%) with periods that usually vary between 8 and 12 seconds, as described by Castaign (1981); the sea waves are the most frequent. The periods are similar throughout the Cantabrian Sea but the wave heights are slightly lower on the eastern side (Ortiz Berenguer *et al.,* 2004). The average significant wave height is 1.0 m and the average for stormy days is approximately 4.0 m.

The extreme waves recorded offshore at the Port of Gijón (MOPT, 1992), El Musel (central Asturian coastal area), with height parameters (H_S) increasing from 7.3 m for 10 years, to 9.5 m for 500 years, and even more when the heights are Hs-90%. Based on the WANA point 1062074 (Puertos del Estado) from 2000 to 2012, the dominant waves are from NW, and to a lesser extent, the first quadrant, N and NE (Fig. 5A).

In this case, the waves coming from the sea only affect the outer mouth, but waves generated into the bay, can affect the inner environments. The dimensions and direction of propagation of these inner-generated waves depend mainly on the fetch and the relative movement between winds and tidally displaced water bodies.

River discharge

The Nansa River, 46 km long, is born in the northern watershed of the Cantabrian Range, draining a hydrographic surface area of 429.50 km^2. Several dams and artificial channels were constructed after 1950: the upper dam of La Cohilla and the lower dam of Palombera have capacities of 12.33 and nearly 2.0 hm^3, respectively. From the lower final dam (14.2 km from the estuarine head) the average (8.7 m^3/s), maximum (137.7 m^3/s) and minimum (0.585 m^3/s) runoffs have been obtained.

The water flow varies greatly over time and between locations. During the summer, the flow is low; in autumn and spring, it is high. The highest monthly averages correspond to December and February (maximums of 15.5 and 14.9 m^3/s, respectively), whereas the lowest monthly averages are associated with the dry season or anticyclonic conditions (July and August) when the average monthly flow is 1.8 m^3/s. The data obtained from *Comisaría de Aguas del Norte de España* (Ministerio de Fomento) over several periods (1940-41 to 1982-83; 1970-71 to 1994-95; 1998-99 to 2010-2011) have been used to calculate the fluvial runoff at the upper tidal limit of the estuary (Table 3).

Tidal propagation

The astronomical tide on the Cantabrian coast has a semidiurnal character and moves from W to E, with a lag of several minutes and increasing in height several centimetres. On this coast, tidal ranges vary from 1.00 m during neap tides to 4.65 m during spring tides, but mesotidal ranges (2.0-4.0 m) are more frequent (about 68.3% of tides) with an average range of about 2.47 m (2010 tide gauge at the Gijón Port), This region can be defined as "low mesotidal" during neap tides and "high mesotidal" during spring tides. The M2 harmonic component has the largest amplitude in the Cantabrian Sea (González *et al.,* 2004).

FLUVIAL VOLUME

	Average	Minimum	Maximum
m^3	439,828.59	35,723.61	142,838.13

TIDAL VOLUME

	Average tides	Neap tides	Spring tides
m^3	1,292,116.70	79,6394.60	1,787,838.80

Table 3. Fluvial water supplied by the Deva River at the upper estuary tidal limit. Data obtained by *Comisaría de Aguas del Norte de España* (Ministerio de Fomento). Below, the tide volume based on tide charts of El Musel Port, Gijón, from the Spanish Service of Puertos del Estado.

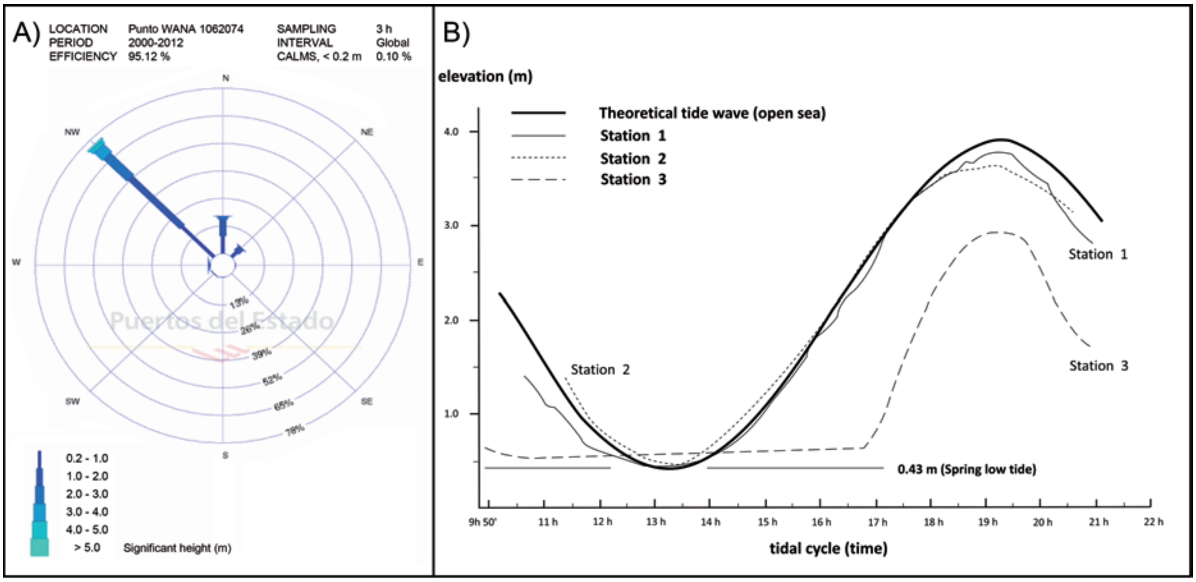


Fig. 5.- A) Prevailing waves from 2000 to 2012 (WANA point 1062074-Puertos del Estado). B) Evolution of the tide wave upstream in Tina Menor estuary, recorded in three stations along the estuarine margins, including the theoretical tide wave and that obtained from the El Musel Port (Gijón)..

The time-height curves were obtained from several tidal measurement stations in 2011 (Fig. 5B) during a spring tide. This tide was selected because the currents are stronger and easily recognisable. The tidal range calculated for this date was 3.09 m but the open coastal tidal range was 3.29 m. The tides propagate from the open sea to the inner estuarine limit and tend to be depressed once inside the estuary due to the joint effects of the narrow mouth inlet, bottom friction and river flow. Therefore, the wave geometry gradually becomes increasingly irregular and asymmetric, decreasing the upstream range. Moreover, there is a delay from the mouth to the inner estuarine limit of approximately 45 minutes. According to the classification of Le Floch (1961), the Tina Menor estuary can be considered as hyposynchronous because the tidal wave encounters friction along the bottom as well as an adaptation processes to the varying margins, decreasing and dissipating the wave (and its range) upstream. Subsequently, the wave geometry is then relatively constant with the appropriate asymmetry throughout the estuary. The tide dissipates about 5 km from the mouth, in conditions of spring tides and low fluvial runoffs.

Salinity cycles

The recorded salinity of the water column during a tidal cycle exhibits a vertically homogeneous saline structure in the mouth (Fig. 6). Therefore, including the surface salinities distribution is useful when deducing the water mixture trends related to the main ebb and flow currents (Fig. 7). In the vertical profiles, the records indicate less saline water during the half rising tide (Figs. 6 and 7A) than during high tide (Figs. 6 and 7B), decreasing again when the tide is falling (Figs. 6 and 7C); furthermore, the measured records are lower during low tide, only in the main channel.

The half rising tide is characterised by saline waters intruding from the open sea along the western outer area (Fig. 7A), adjusting to both margins of the main channel. Upstream, where the incoming water column is still minimal (Fig. 6), the flow is restricted to the main channel.

During high tides (Fig. 7B), the *Tidal flat* and *Upper channel* areas are dominated by salt wedge conditions and fresh water is retained upstream by the tidal flood. The outer belt exhibits a saline vertical record in the western margin (seawater) and a salt wedge in central and eastern areas due to the extrusion of mixed waters. The *Bay* and *Mouth complex* are better represented by a vertically homogenous saline structure (Fig. 6). When the tide falls, almost all of the water salinity data assume a vertically homogeneous structure, which is more saline to the western side of the *Mouth complex* and slightly fresher on the same bank in the inner estuary. At low tide, the fresh and slightly fresh waters migrate to the mouth, evolving upstream to a mainly salt-wedge estuary in the channels. At this point, the water mixing behaviour is more complex, including phases and sites with partial mixing (Figs. 6 and 7C).

Using Simmons (1955) criteria, the minimum runoff with all tides conditions reproduces a vertically homogeneus mixed type estuary, however, maximun runoff and neap-av-

Q_F/Q_T	*Maximum runoff*	*Minimum runoff*	*Average runoff*
Spring tides	0.798	0.020	0.246
Neap tides	1.793	0.044	0.552
Average tides	1.105	0.027	0.340

Table 4. Relationships between tidal prism (saline) and river discharge (fresh water), in relation with the water volumes. Q=N (value, according Simmons (1955).

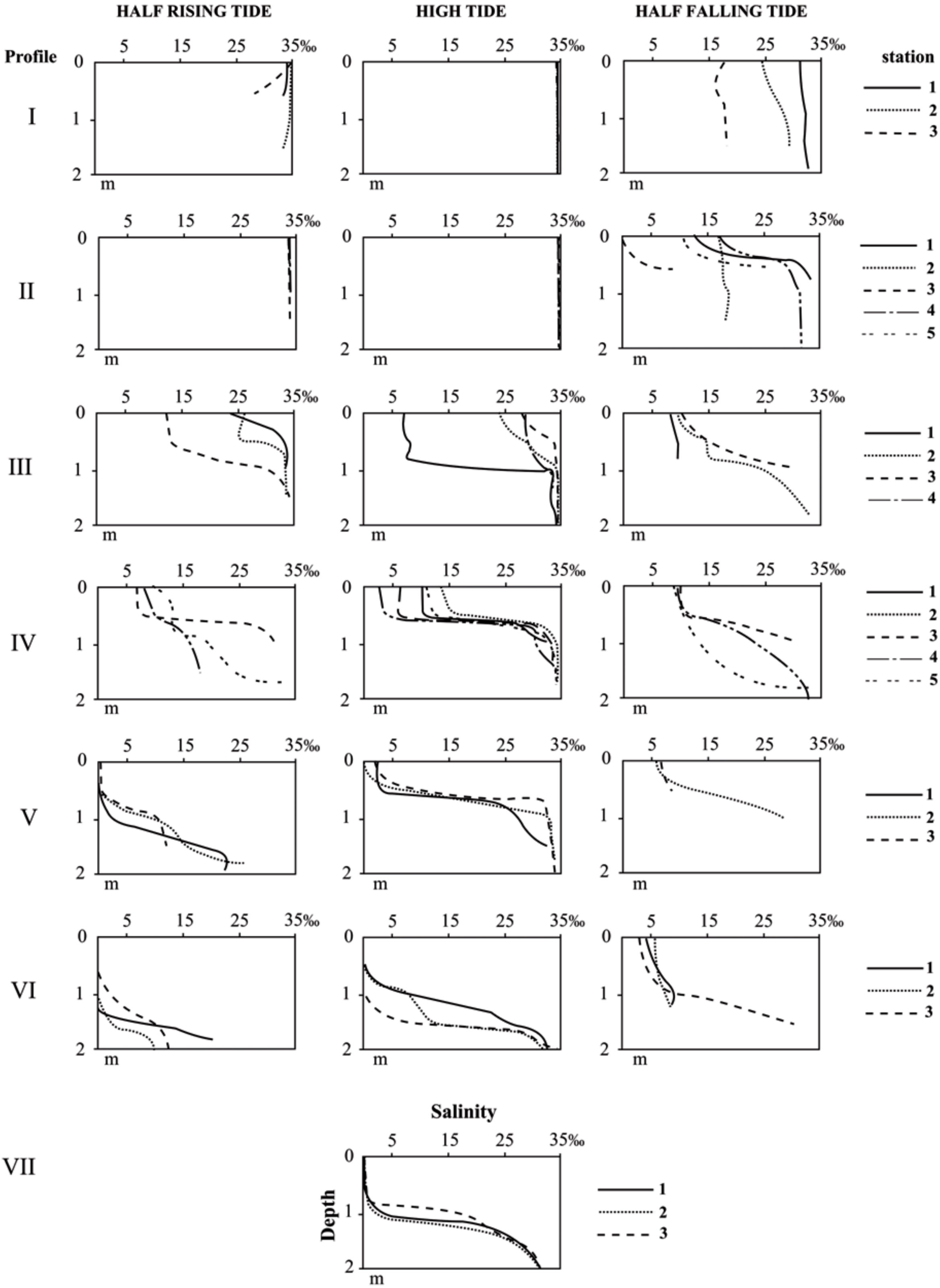


Fig. 6.- Vertical salinity records from the surface to the bed at three tide phases: half rising tide, high tide and half falling tide, for the seven profiles selected in the estuary.

erage tides represent a salt wedge estuary and partially mixed type for average conditions (Table 4).

Tidal current distribution

The current velocity was recorded simultaneously with salinity in the water column during a tidal cycle. In a general

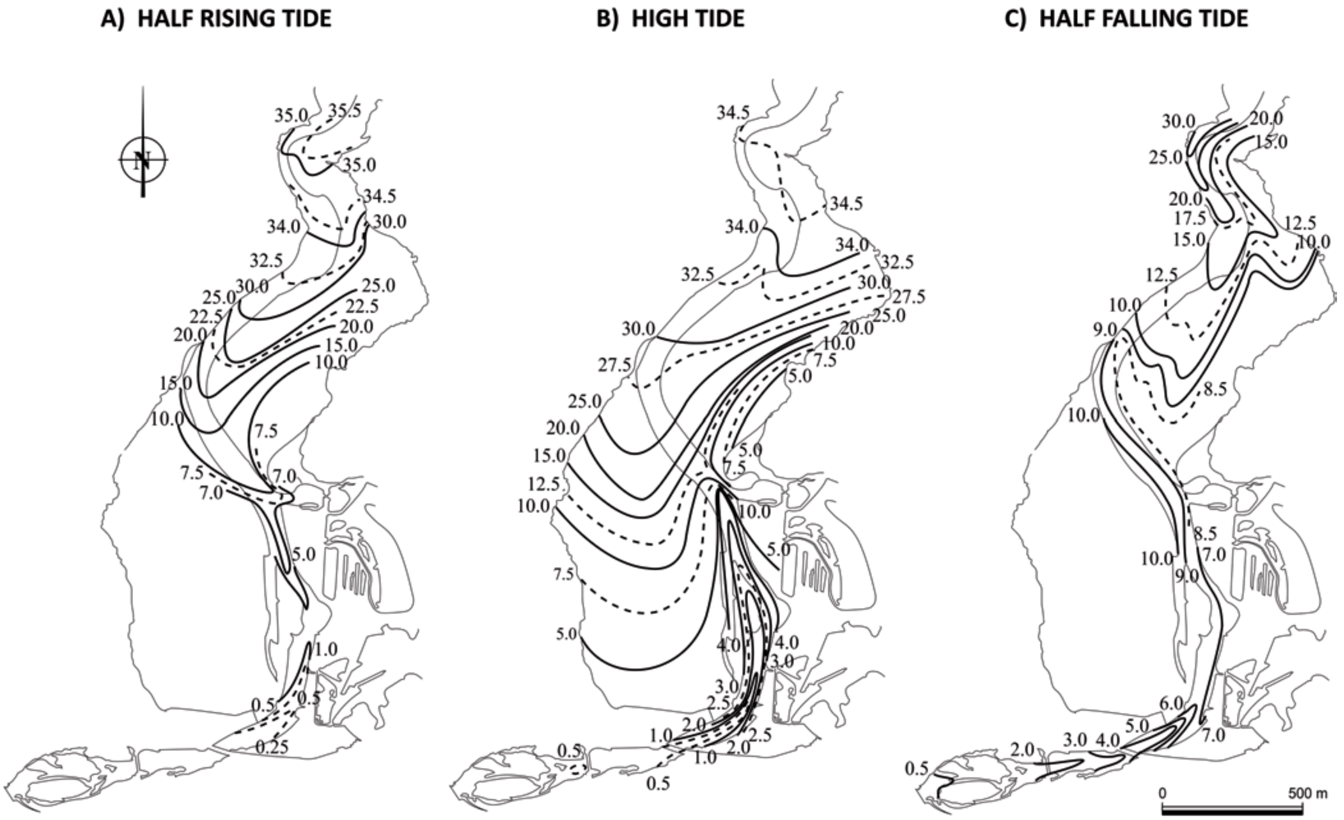


Fig. 7.- Distribution of surface salinity, representing contour lines along a tidal cycle.

way, we can observe that the values of velocity are higher during the flood ebb than during the flood, in the inner system, whereas in the flood tidal deltas and spill-over lobes (*Bay* and *Mouth complex*) the dominant current is the flood. The maximum ebb current are registered along different sectors the main estuarine channel where the maximum current is about 1.5 m/s (Table 5). It is also in this environment where the asymmetry of the flows is higher, increasing to the innermost tracks. In the mouth complex, a wider section of the channel induces a decreasing velocity during the ebb.

A simple circulation model is suggested, taking into consideration the direction and velocity of currents (Fig. 8). Based on the recorded data, the flow velocities are grouped into three relative categories: strong (≥1.0 m/s), moderate (0.5-1.0 m/s) and weak currents (≤0.5 m/s). Furthermore, the bottom currents have been included applying the same categories. However, some velocity records exceed 1.50 m/s, especially in the inner inlet during the half rising tide and during relatively long time intervals in the half falling tides; there is also a nearby fluvial influence.

During low tides, the mixed waters (mainly fluvial) flow through the main channel and tidal creeks, which function now as tributary channels, with a unidirectional ebb. That is characteristic of a dynamic fluvial model (Fig. 8A); the flow occurs primarily in the inner estuary where the fluvial influence is strong, that increases during low tides. The most intense currents are generally detected in the main channel and where the tributaries join the main channel. In addition, the currents have a significant effect in the inner inlet and in a sector situated just to the south of the *Tidal flats*.

When marine waters begin to penetrate during the rising tides, the strongest current occur in the inlet, through the external flood tidal-delta and the spill-over lobe (Fig. 8B). During these periods, a surficial fresh and mixed water plume flows toward the eastern margin. Once overcome the rocky confinement, the main channel is forced to change from the eastern to western side. Simultaneously, the marine waters intrude into the main channel, but in the outer *Bay*, a persistent strong flow current is diverted to the SE corner by the internal flood tidal-delta. In the southern *Bay* area, this current meets the opposite inertial ebb current of the mixed waters from the

SECTOR	ENVIRONMENT	MAX. FLOOD (m/s)	MAX. EBB (m/s)
Mouth complex	Main channel	0.7	0.85
Bay	Main channel	0.55	1.3
	Flood tidal-deltas	1.5	1.1
	Spill-over lobes	1.4	0.9
	Sandy tidal flats	1.15	0.8
Tidal flats	Main channel	0.75	1.4
	Muddy tidal flats	0.6	1
Upper channel	Main channel	0.25	>1.5
	Bars	0.1	>1.5
	Fluvio-tidal flats	0.1	0.6

Table 5. Maximum tidal currents (ebb and flood) measured at the different estuarine morpho-sedimentary units.

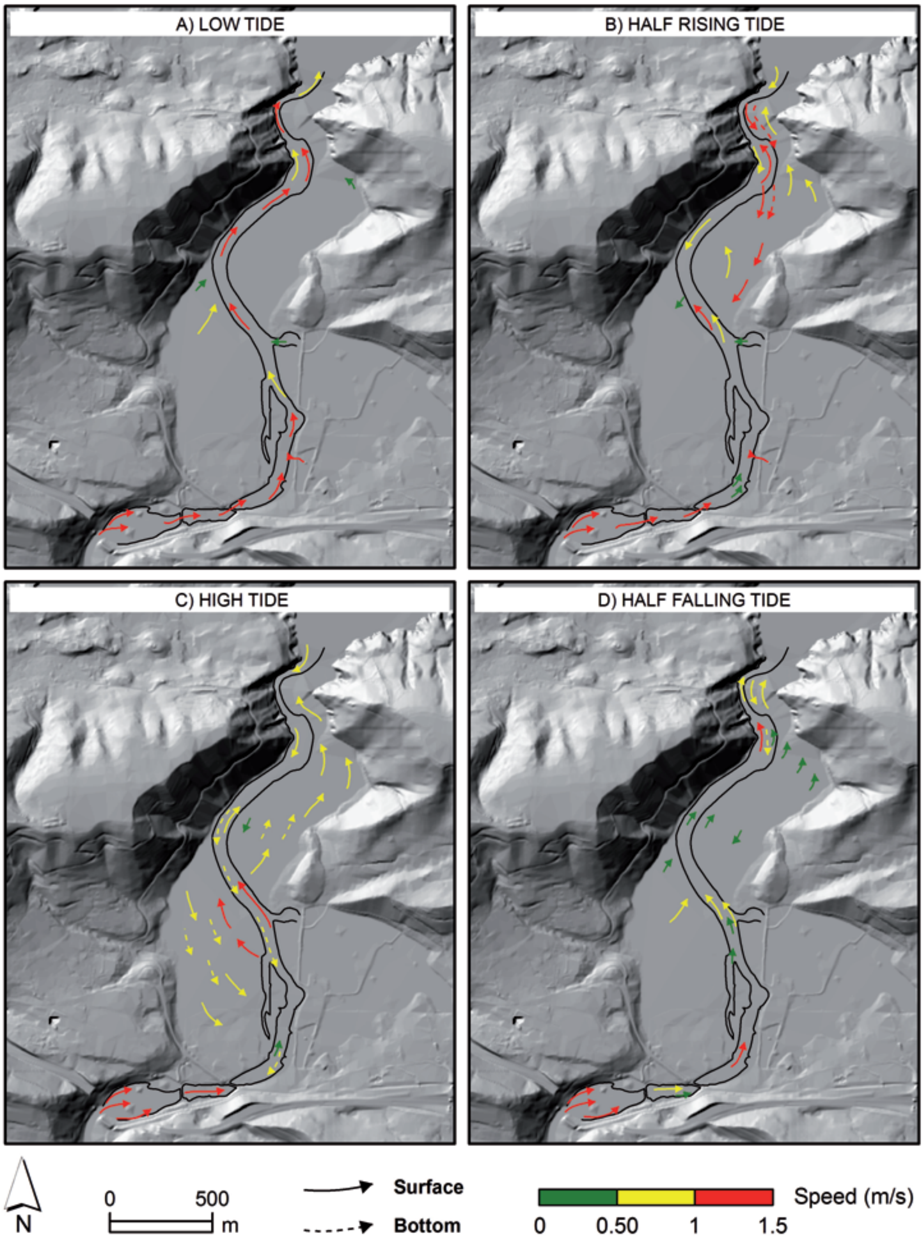


Fig. 8.- Simplified scheme of representative currents recorded in the water column during a tidal cycle. Simplistically, each tidal stage extends over a range of just under 1.5 hours.

inner estuary that are extruded from the main channel. For this reason, the half rising tide represents the most important moment for forming the bay structures (Fig. 8B).

During high tides, likewise, stronger currents are recorded on the western bank of the main channel. Moderate currents flow along the eastern side of the *Bay* to the mouth and the sweeping *Tidal flats* to the inner estuary (Fig. 8C). A cell of counter-clockwise rotation is registered throughout the estuary and is very evident in the mouth and the bay. The rotation is lower in the main channel of the inner estuary.

During the half falling tide, the mixed waters are extruded from the main channel and into the northern area of the *Bay* through the eastern and central areas. Outside of the estuary mouth, the currents tend to be conducted to the exposed beach through the inlet (Fig. 8D). Anticlockwise rotation only forms in the *Mouth* and the outer part of the *Bay* and the remaining areas present only unidirectional ebb currents.

5. Hydrodynamic controls of sedimentation: a morpho-sedimentary conceptual model

The dynamics of rock-bounded estuaries have been previously described almost exclusively in high latitude regions, i.e. in British Columbia (Milliman, 1980), Oregon (Boggs and Jones, 1976), New England (FitzGerald *et al.,* 2002) or Kennebec (Fenster *et al.,* 2001) but there are also some studies regarding Iberian Peninsula estuaries, i.e. Douro (Portela, 2008) and Guadiana (Garel *et al.,* 2009, Morales *et al.,* 2014). The tidal and fluvial currents are the more energetic dynamic agents, sharply conditioned in this estuary by the outer geometry of the former rocky valley. Specifically, the narrow rocky confinement and sinuous trace of the mouth and outer *Bay* are the major factors that control the dynamics and the distribution of the sedimentary and morphological units in the *Mouth complex* and *Bay*. The sedimentary transport and sedi-

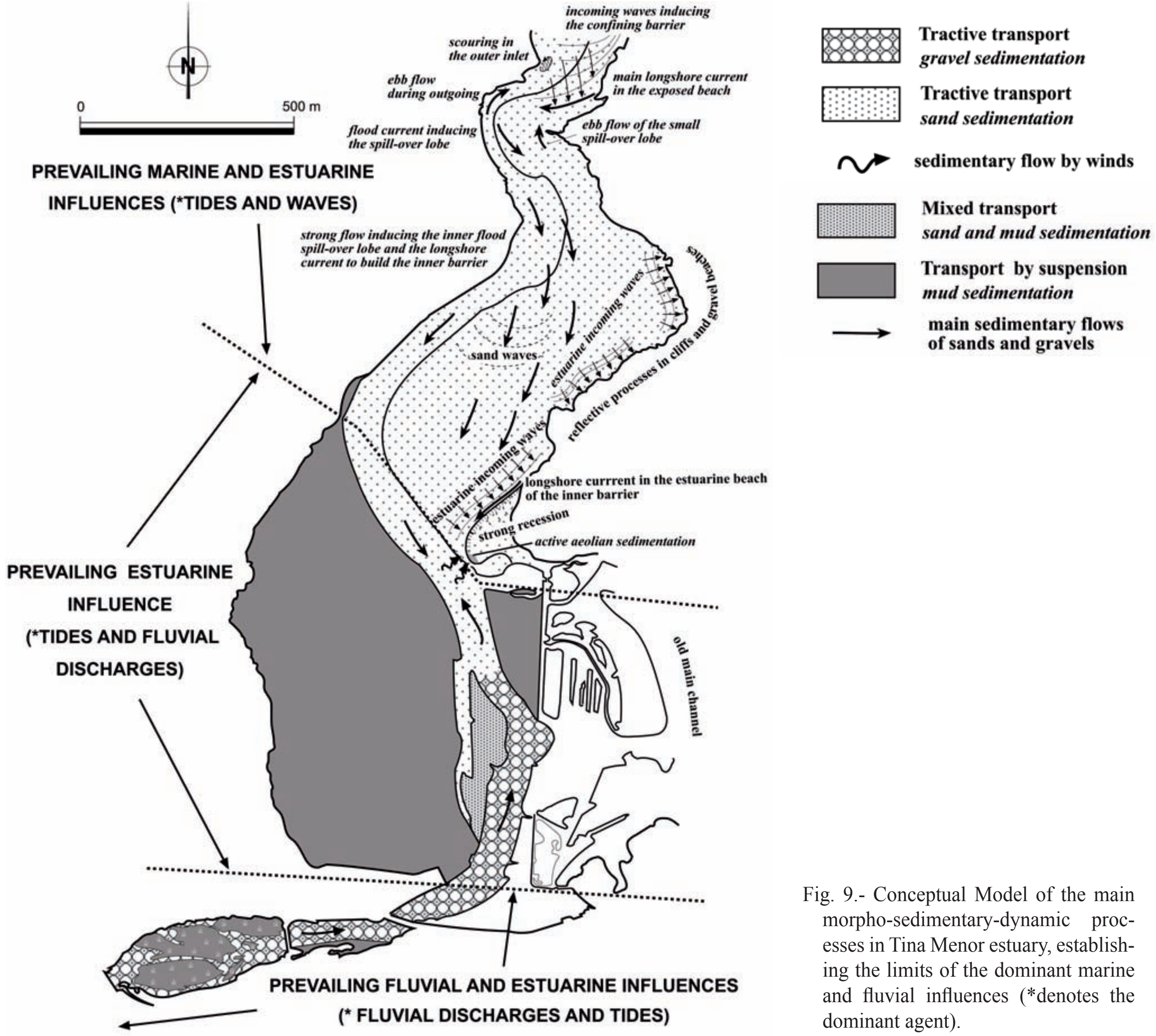


Fig. 9.- Conceptual Model of the main morpho-sedimentary-dynamic processes in Tina Menor estuary, establishing the limits of the dominant marine and fluvial influences (*denotes the dominant agent).

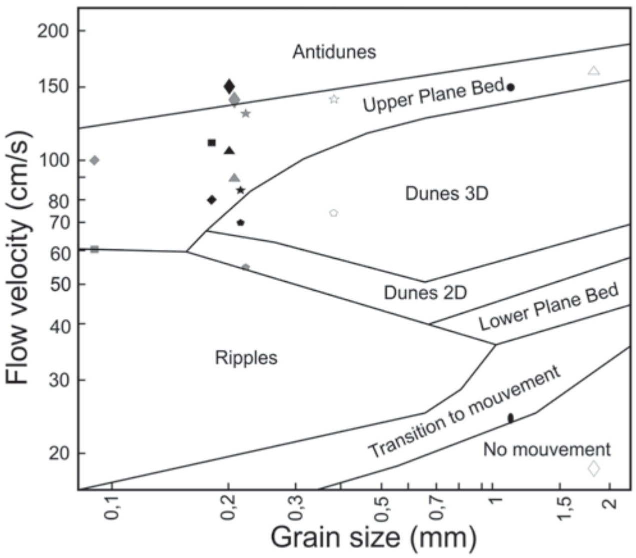
ment distribution vary with the tidal cycle, and over a larger timescale, depending on the seasonality of fluvial discharges, eustatic variations and anthropic interventions.

Salinity, velocity and currents direction data can be understood through a simple morpho-dynamic conceptual model (Fig. 9). That allows the establishment of correlations between surficial sedimentary distribution and water circulation. Three main areas are identified where marine and fluvial influences are prevailing (Fig. 9), which from the estuarine mouth to the head are summarised in the following sections.

5.1. Dynamics on the marine estuary (mouth complex and bay): tides and waves

Tides and their associated ebb and flow currents are the most important dynamic agents in the outer estuary. In the outer inlet, a deep scour forms to replace the mouth bar where the strong ebb currents are dissipated. In addition, the wave action on the exposed beach generates longitudinal currents toward the inlet on the western side. The action of waves in the front of the exposed beach are reflected in the presence of symmetric straight-crested ripples in the front of the beach.

Clearly the main channel is a permanent dynamic and morpho-sedimentary unit. This outer estuarine segment is included in the *Mouth complex* and *Bay* and is characterised by the morphological control of the old incised valley. The flood currents are normally higher than the ebb ones, so the most efficient hydrodynamic track is located near the western bank according with the situation more favourable for the ebbing flows. However, the channel may occasionally migrate to the eastern bank after a strong river flood, but this situation is always temporary, lasting only until the channel migrates again gradually to the western bank once the normal river flow is restored. From a sedimentological point of view this environment is constituted by well sorted fine sands. No bedforms were observed in the main channel, but according with the present grain size and tidal current velocities represented in a diagram of Harms *et al.* (1975), dunes 3D would



		EBB	FLOOD
MOUTH COMPLEX	MAIN CHANNEL	★	⬟
BAY	MAIN CHANNEL	★	⬟
	FLOOD TIDAL DELTAS	▲	◆
	SPILL-OVER LOBES	▲	◆
	SANDY TIDAL FLAT	◆	■
TIDAL FLATS	MAIN CHANNEL	☆	⬠
	MUDDY TIDAL FLATS	◆	■
UPPER CHANNEL	MAIN CHANNEL	●	⬮
	BARS	△	◇

Fig. 10.- Bedform stability conditions for the dominant sediment under the maximum ebb and flood velocities measured during the studied tide and represented in the diagram of Harms *et al*. (1975).

be developed under flood conditions whereas it would turns upper plane bed during ebb conditions (Fig. 10). That occurs similarly in some Irish estuaries (Cooper, 2006), the Mersey estuary (Blott *et al.,* 2006) and other Atlantic estuaries, but in this case, the waves are refracted in the rocks located in the western estuarine mouth, generating a longshore current to the E toward the Bay.

Into the *Bay*, most dynamic activity occurs during the flood tidal currents, which are clearly stronger than the ebb in all the intertidal environments. Only the main estuarine channel maintains the dominance of ebb currents. During flood conditions, the flood-tidal deltas with several attached spill-over lobes are activated. Some of these lobes are oriented upstream, while a drift current flows SE due to the rocky outcrops to the W that change the direction of the current in the inner estuarine valley. These persistent currents, moves along a strip on the eastern margin of the *Bay* and this current is the responsible of the inner barrier morphology. These flood tidal deltas and lobes are also formed by well sorted fine sand and flood oriented medium 2D and 3D dunes have been observed. Nevertheless, the expected bedforms according the hydro-sedimentary characteristics of the environment (Harms *et al.,* 1975, diagram) would be plane bed during the maximum ebb and antidunes during the maximum flood, both corresponding with a higher flow regime than the indicated by the observed bedforms. This disagreement would be explained from a hydrodynamic point of view if the maximum current do not act during enough time to get the stable forms. So, during the maximum energy peaks, the extreme currents only rework the crests of bedforms developed under lower flow regimes.

The tidal flood, diverted to the SE corner by internal flood-tidal delta results in a sedimentary drift supplying sediment to develop the inner barrier; the shape of this barrier has accreted gradually to the S. In addition to the tidal action, the dominant NW winds generate small waves into the estuary during high tides, activating both the gravelly and sandy estuarine beaches. Consequently, these local waves also modify the direction and velocity of the tidal currents.

5.2. Dynamics on the inner estuary (tidal flats and main channel): tides and fluvial discharges

The sediment-transport patterns observed in this sector of the estuary are mainly controlled by tidal currents and are seasonally reinforced by the riverine flow in a similar way as the Kennebec estuary (Fenster *et al.,* 2001). The main direction of the observed bedforms and the measured tidal currents show an ebb-dominated tidal regime, with patterns of net bedload transport towards the mouth. On the contrary, the most singular circulation patterns occur during some moments of the flood period, when anticlockwise spins have been observed (High tide. Fig. 8C). According with several authors in other similar estuaries these gyres can be interpreted as a result of the Coriolis effect (Heniche *et al.,* 2000; Friedrichs and Hamrick, 1996; Valle-Levinson *et al.,* 2000; Huijts *et al.,* 2011).

In addition, the intrusion of marine waters during rising tides induces the presence of a salt wedge and a turbidity maximum that enter into the estuary to be finally located on the inner tidal flats. In this area, the main channel maintains the salt wedge in an outer position, because is the environment with higher ebb-currents, whereas on the muddy tidal flats the saline waters penetrate until innermost areas. It is just in the muddy tidal flats where the mixing waters are responsible of an intense flocculation process that generates the muddy particles finally deposited on the flats.

A special dynamic situation occurs during extreme fluvial floods. These discharges act predominantly on the active *Tidal flats* located on the western side where normally the energy level is low. The events of river discharges occur through the main channel after the human reclamation of the eastern *Tidal flats*. From a sedimentological point of view, in this estuarine segment, the tidal influence might be the flooding of these broad areas; the mud settles during high tides. However, the activity best represented by the main channel is the supply of sands and gravels during river floods.

5.3. Dynamics on the fluvial estuary: fluvial discharges and tides

Mainly in the *Upper channel* zone, the fluvial discharges are the most important dynamics, generating flat gravel beds, as well as emerged and submerged ebb bars. Therefore, the fluvial influence is evident, although there is a degree of localised remobilisation during the incoming tides because the volume of water stored until high tide is greater than that of the river flow, generating intense ebb currents. These strong currents are more apparent in this inner zone, nevertheless the remaining zones receive minor adjustments under low and average flow fluvial regimes. The tidal influence is also present in this sector of the estuarine channel during low discharge periods, but with a very high tidal asymmetry. Whereas the flood tidal currents do not get the treshold to move the dominant sediment, the ebb ones can transport the available sediment (poor or moderately poor very coarse sands) in an upper plane bed configuration.

6. Discussion and Conclusions

This paper details the study of all of the morphological (confinement) and dynamic factors (waves, tides and river discharge) that exist in the estuary, allowing for the proposal of a dynamic conceptual model for other rock bounded estuaries.

According to Ryan *et al.* (2003) and Dalrymple *et al.* (1992) criteria, Cantabrian estuaries would be wave-dominated estuaries (WDE) from morphological and dynamic points of view. For these authors, waves are important and generate a confining barrier in the marine estuary, whereas in other estuarine zones, tidal currents and fluvial discharges are the most important dynamic agents. Nevertheless, with the present data, we cannot asseverate that Tina Menor is a wave-dominated estuary. Large cores and a facies model will be necessary to demonstrate this fact. Despite this general classification by Ryan *et al.* (2003), the Tina Menor estuary may have a barrier estuary morphology (Sloss *et al.,* 2006), or may be a drowned valley barred estuary (Copper, 2006), however, a proper barrier has not developed, only a beach as a continuity of the flood-delta tidal ramp. The mouth of the estuary is confined by bedrock headlands, which results in strong tidal and wave induced currents leading to poor barrier development. In this case, the presence of a real barrier is not essential for developing this kind of estuaries when another morphological element (such as rocks) is available to limit wave action in the estuary, creating a tidal and fluvial dominated estuary similar to the morphogenetic classification proposed by Perillo (1995). Therefore, these estuaries are rock-bounded estuaries or incised valleys according to Posamentier and Vail (1988).

In this case, Tina Menor is a narrow mesotidal partially infilled estuary, similar to most of the Cantabrian estuaries; it is hyposynchronous and predominantly of partially mixed type, according to the stratification and characteristics of the salinity distributions (Pritchard, 1955; Simmons, 1955; Cameron and Pritchard, 1963). The narrow rocky mouth of this estuary is bounded by Palaeozoic quartzite and limestone outcrops that control the distribution of the confining barrier, submerged during high waters. On the other hand, the currents and sediment input in the major sandy areas and the Nansa River discharges also provide a strong influence in the general behaviour of the estuary. Indirectly, the characteristics of the estuarine mouth geometry are highly important; therefore, in a morpho-sedimentary context, the micro and mesotidal estuaries are commonly confined by barriers (Hayes, 1975).

The difference of this estuary with other mesotidal estuaries is the great bounded valley with a sedimentation rates inside of 0.1-0.8 cm yr^{-1} (Alonso González, 2015), leading to clearly developed sandy bed morphologies. In many estuaries, the transition from a morphosedimentary unit to another is normally not as clear, but in this case, the structures are linked one after the other according with the dominant process and can be clearly mapped. This allows a division of the estuary into four distinct zones, gradually passing from the inner estuary mouth to the river influence in the inner zone of the estuary: *Mouth complex*, *Bay*, *Tidal flats* and *Upper channel*. Most Atlantic estuaries have four differentiated zones, in contrast to others authors who propose three zones, such as Dionne (1963) and Bird (1967); according to tidal and salinity characteristics, Wright (1977), Nichols and Biggs (1985) and finally Allen (1991) distinguish between three areas morphologically similar to the four proposed in this paper. The cause for this difference is the partial state of infilling of these estuaries, where the innermost part of the central basin present the characteristics of a more advanced infilling whereas the in the outer part the stage of infilling is lower.

Based on this zonation and the morphology, the narrowing of the rocky mouth governs the unique dynamics and distributions of the main morpho-sedimentary units in the external area. The drift currents from the incoming waves transport sediments in a south westerly direction, creating the incipient barrier after breaking down the two-layered flow during the spring and neap tides (Chawla *et al*., 2008), as well as during the same tidal cycle with less saline ebb current surface and marine current flows. In this case, the barrier is poorly developed and is anchored on the eastern side due to the dominant incoming waves from the NW. Other difference is the absence of a clear ebb-tidal delta as a result of the progradation of the lower estuary. This is the case of other wave-dominated systems like the Senne estuary (Lesourd *et al.,* 2001; Waeles *et al.,* 2007). In our case, only a narrow frontal ebb-lobe is developed showing the dominance of the waves in this sectorThe dynamics in the *Bay* are characterised by the presence of various sandy flood-tidal deltas and spill-over lobes with varying geometries. In Tina Menor multi-lobate flood-tidal deltas are generated due to the rocky narrowing of the mouth, replacing the spit. In this case the tidal energy is dissipated to enter the estuary and inhibits the formation of a wide flood-tidal delta, similar to other mesotidal Cantabrian estuaries, such as Foz (Díez *et al.,* 2006), Eo (Flor *et al.,* 1992), and

San Vicente de la Barquera (Flor-Blanco *et al.,* 2015). The currents through the sinuous valley geometry and the internal flood-tidal delta distribute sediments and flow toward the inner estuary mainly during rising tide, strongly influenced by the western outcrop (Figs. 4 and 9). The presence of this outcrop trigger the movement of the channel water and sands toward the southeastern side, promoting the construction of the inner barrier (El Sable). The reason for the development of an inner barrier (estuarine beach) is the accumulation here of the excess of sediment coming from the inner flood tidal-delta. The sand is transported by local waves to the bar, across the flat, during the spring high tides. The absence of a real barrier in the mouth also facilitates the entrance of refracted waves into the estuary during high tides. In this sector, the main channel is located in the western area until it meets the *Tidal flats*; at this point, the opposing currents entering the mouth and the ebb currents and the river discharge force this channel over to the eastern side of the *Bay*, joining it with the *Upper channel*.

Along the tidal cycle, a general levorotatory circulation acts throughout the estuary, the current flows along the left side, however the ebb current flows along the right. This circulation behaviour is detected at high tide in the upper channel limit and the marshes and only at the mouth at low tide. The exception occurs during the half rising tide, when the flowing currents are diverted toward the eastern side. This effect is interpreted as a result of a deflection of the flow current along the central southeast direction due to the western rocky outcrop and because the ebb current in the east is moderate or residual. Within rock-bounded estuaries with the same features, the Coriolis effect in the surface layer has also been observed in several studies in the Iberian Peninsula: in the Arosa Ria estuary (Roson *et al.,* 1997), in the mouth of the Tinto and Odiel estuary in Huelva (Ojeda *et al.,* 1995) and in the outer mouth of the Eo estuary (Piedracoba, 2005). This effect has also been observed in larger macrotidal estuaries in Australia (Ryan *et al*., 2003) and in the Yangtze estuary (Li *et al.,* 2011).

In the innermost sectors, the maximum salinity is reached during high tides, revealing the process of the intruding saline waters. These processes of mixing water generate a flocculation process responsible of the turbidity maximum and the deposition of mud particles on the muddy tidal flats. The presence of these inner muddy tidal flat demonstrates that the estuary is in and advanced phase of its ephemeral geological life cycle. In his case, aggradation processes dominated the inner system from the head of the embayment to the mouth (Duck *et al.,* 1995).

Generally, estuaries are ecological valuable areas and the Tina Menor is one of the most natural examples for this type of ecosystem, barely disturbed by human activities. Consequently, the morphodynamic knowledge and the behaviour of the estuary is very important for its future management and morphology effects by sea level changes; for validating the theoretical models, and to preserve the ecology present therein and in similar estuaries.

Acknowledgements

With thanks to Saltos del Nansa, S.A., for the Nansa River data, and to the Mapping Service of Cantabria. We are grateful to the reviewers for their suggestions.

References

Allen, G.P. (1991): Sedimentary processes and facies in the Gironde estuary: a recent model for macrotidal estuarine systems, In: Smith, D.G., Reinson, G.E., Zaitlin B.A., Rahmani, R.A. (Eds.), *Clastic Tidal Sedimentology*. Can. Soc. Petrol. Geol. Mem. 15, 29-40.

Alonso González, M. (2015): Cantabrian estuary sediment analysis by gamma espectroscopy of 210Pb and 137Cs: sedimentation rate, dating and biodiffusion effects. 50 pp. Trabajo Fin de Grado. Facultad de Ciencias. Universidad de Cantabria. http://repositorio.unican.es/xmlui/handle/10902/7116

Blott, S.J., Pye, K. (2001): Gradistat: a grain size distribution and statistics package for the analysis of unconsolidated sediments. *Earth Surface Processes and Landforms* 26(11), 1237-1248. doi: 10.1002/esp.261

Blott, S.J., Pye, K., van der Wal, D., Neal, A. (2006): Long-term morphological change and its causes in the Mersey Estuary, NW England. *Geomorphology* 81(1-2), 185-206. doi:10.1016/j.geomorph.2006.04.008

Bird, E.C.F. (1967): Coastal lagoons of southeastern Australia, in: Jennings J.N., Mabbutt, J.A. (Eds.), *Landform Studies from Australia and New Guinea*. Cambridge Univ. Press, 365-386.

Boggs, W.S., Jones, C.A.J. (1976): Seasonal reversal of flood-tide dominated sediment transport in a small Oregon estuary. *Geological Society of America Bulletin* 87, 419-426. doi: 10.1130/0016-7606(1976)87<419:SROFDS>2.0.CO;2

Bruschi, V.M., Bonachea, J., Remondo, J., Gomez-Arozamena, J., Rivas, V., Mendez, G., Naredo, J.M., Cendrero, A. (2013): Analysis of geomorphic systems response to natural and human drivers in northern Spain; implications for global geomorphic change. *Geomorphology* 196, 267-279. doi:10.1016/j.geomorph.2012.03.017

Burningham, H. (2008): Contrasting geomorphic response to structural control: the Loughros estuaries, northwest Ireland. *Geomorphology* 97, 300-20. doi:10.1016/j.geomorph.2007.08.009

Burningham, H., Cooper, J.A.G. (2004): Morphology and historical evolution of north-east Atlantic coastal deposits: the west Donegal estuaries. *Journal of Coastal Research* SI. 41, 148-159.

Cameron, W.M., Pritchard, D.W. (1963): Estuaries, In: Hill, M.N., (Ed.), *The Sea*. Wiley, N.Y., 2, pp. 306-324.

Castaing, P., Allen, G. P. (1981): Mechanisms of seaward escape of suspended sediment from the Gironde: a macro tidal estuary in France. *Marine Geology* 40, 101-118. doi:10.1016/0025-3227(81)90045-1

Chaumillon, E., Proust, J.N., Menier, D., Weber, N. (2008): Incised-valley morphologies and sedimentary-fills within the inner shelf of the Bay of Biscay (France): a synthesis. *Journal of Marine systems* 72(1), 383-396. doi:10.1016/j.jmarsys.2007.05.014

Chawla, A., Jay, D.A., Baptista, A.M., Wilkin, M., Seaton, C. (2008): Seasonal variability and estuary-shelf interactions in circulation dynamics of a river-dominated estuary. *Estuaries and Coasts* 31, 269-288. doi: 10.1007/s12237-007-9022-7

Cooper, J.A.G. (2001): Geomorphological variability among microtidal estuaries from the wave-dominated South African coast. *Geomorphology* 40(1), 99-122. doi:10.1016/S0169-555X(01)00039-3

Cooper, J.A.G. (2006): Geomorphology of Irish Estuaries: Inherited and

Dynamic Controls. *Journal of Coastal Research* SI 39, 176-180.

Dalrymple, R.W., Zamts, B.A., Boyd, R. (1992): Estuarine facies models: conceptual basis and stratigraphic implications. *Journal of Sedimentary Petrology* 62, 1130-1146.

Dias, J.M.A., Gonzalez, R., Ferreira, O´. (2004): Natural Versus Anthropic Causes in Variations of Sand Export from River Basins: an Example from the Guadiana River Mouth (Southwestern Iberia). Rapid Transgression into Semi-enclosed Basins. *Polish Geological Institute Special Papers* 11*,* 95-102.

Díez J.J., Negro V., Fernández P. (2006): Further studies for stabilizing the entry channel to Foz fishing port, Lugo. *Journal of Coastal Research* 22, 710-719. doi: 10.2112/03-0044.1

Dionne, J.C. (1963): Towards a more adequate definition of the St. Lawrence estuary. *Zeitschrift fur Geomorphologie* 7, 36-44.

Dronkers, J. (1986): Tidal asymmetry and estuarine morphology. *Netherlands Journal of Sea Research* 20(2-3), 117-131. doi:10.1016/0077-7579(86)90036-0

Duck, R.W., McManus, J., Díez, J. (1995): Comparative study of two largely inflilled estuaries: the Eden Estuary (Scotland) and the Ria de Foz (Spain). *Netherlands Journal of Aquatic Ecology* 29, 203-210. doi: 10.1007/BF02084217

Evans, G., Prego, R. (2003): Rias, estuaries and incised valleys: is a ria an estuary?. *Marine Geology* 196(3), 171-175. doi:10.1016/S0025-3227(03)00048-3

Fenster, M.S., FitzGerald, D.M., Kelly, J.T., Belknap, D.F., Buynevich, I.V., Dickson, S.M. (2001): Net ebb sediment transport in a rock-bound, mesotidal estuary during spring-freshet conditions: Kennebec River estuary, Maine. *Bulletin of Geological Society of America* 113, 1522-1531. doi: 10.1130/0016-7606(2001)113<1522:NESTIA>2.0.CO;2

Fitzgerald, D.M., Buynevich, I.V., Fenster, M.S., McKinlay, P.A. (2000): Sand circulation at the mouth of a rock-bound tide-dominated estuary. *Sedimentary Geology* 131, 25-49. doi:10.1016/S0037-0738(99)00124-4

FitzGerald, D.M., Buynevich, I.V., Davis Jr., R.A., Fenster, M.S. (2002): New England tidal inlets with special reference to riverine associated inlet systems. *Geomorphology* 48, 179-208. doi:10.1016/S0169-555X(02)00181-2

Flor, G. (1995): Clasificación y caracterización de los estuarios asturianos. Proc. IV. Coloquio Internacional sobre oceanografía del Golfo de Vizcaya. O. Cendrero, Olaso. I. (Eds.), pp. 133-141.

Flor, G., Camblor, C. (1990): Dinámica y sedimentación en el estuario de Ribadesella (Asturias, N de España). *Trabajos de Geología* 17, 16-36.

Flor, G., Fernández Pérez, L.A., Cabrera Ceñal, R. (1992): Características dinámicas y sus relaciones sedimentarias en la ría del Eo (Asturias-Galicia, NO de España). *Revista de la Sociedad Geológica de España* 5, 7-25.

Flor, G., Cabrera Ceñal, R., Suárez González, M.A., Iglesias Ortea, P.J. (1998): Aspectos morfológicos, dinámicos y sedimentológicos del estuario del Nalón (Asturias, NO de España). *Trabajos de Geología* 20, 3-37.

Flor, G. Fernández-Pérez, L.A., Menéndez-Fidalgo, R., Martínez Cueto-Felgueroso, E.M., Rodríguez-Casero, G. (1996): Dynamics and sedimentation of the mesotidal estuary of Villaviciosa (Asturias, Northern Spain). *Revista de la Sociedad Geológica de España* 9, 205-225.

Flor, G., Ortea, J.A., Rodríguez-Palacio, M.J. (1998): El componente bioclástico en el sedimento arenoso en el complejo estuarino de Villaviciosa (Asturias, NO de España). *Trabajos de Geología* 20, 129-156.

Flor, G., Flor-Blanco, G. (2014): Raised Beaches in the Cantabrian Coast. In: Gutiérrez, F, Gutiérrez, M. (Eds). *Landscapes and Landforms of Spain*. Springer Netherlands, pp. 239-248. doi: 10.1007/978-94-017-8628-7_20

Flor, G., Rey, J., Flor-Blanco, G. (2015): Dynamics and morpho-sedimentary interactions in the lower mesotidal estuary of Villaviciosa (NW Spain). *Geologica Acta* 13(2), 107-121. doi: 10.1344/GeologicaActa2015.13.2.3

Flor-Blanco G., Flor G. (2009): Aspectos geomorfológicos del tramo inferior del estuario de Villaviciosa (Asturias) en relación con su evolución histórica. *Revista de la Sociedad Geológica de España* 22, 123-136.

Flor-Blanco, G., Flor, G. (2012): Clasificación geomorfológica y características de los estuarios cantábricos (NW de España). In: González-Díez, A. et al (Eds.), *Avances de la Geomorfología en España, 2010-2012*, pp. 315-318.

Flor-Blanco, G., Flor, G., Pando, L. (2015). Morphodynamics, sediments and evolution of the outer portions of the San Vicente de la Barquera estuary (Cantabria, NW Spain), with a focus on anthropogenic influences. *Geologica Acta* 13(4), 279-296. doi: 10.1344/GeologicaActa2015.13.4.2

Folk, R.L., Ward, W.C. (1957): Brazos River bar: a study in the significance of grain size parameters. *Journal of Sedimentary Petrology* 27, 3-26. doi: 10.1306/74D70646-2B21-11D7-8648000102C1865D

Fontan, A. (2001): Estudio integral de los cambios producidos en el estuario de Tina Menor. *Revista Aquatic* 13, 1-27.

Friedrichs, C.T., Hamrick, J.M. (1996): Effects of channel geometry on cross sectional variations in along channel velocity in partially stratified estuaries. *Coastal and Estuarine Studies* 53, 283-300. doi: 10.1029/CE053p0283

Garel, E., Pinto, L., Santos, A., Ferreira, Ó. (2009): Tidal and river discharge forcing upon water and sediment circulation at a rock-bound estuary (Guadiana estuary, Portugal). *Estuarine, Coastal and Shelf Science* 84, 269-281. doi:10.1016/j.ecss.2009.07.002

González, M., Uriarte, A., Fontán, A., Mader, J., Gyssels, P. (2004): Oceanography and Marine Environment of the Basque Country. *Marine Dynamics*, In: Borja, Á., Collins, M. (Eds.), Elsevier Oceanographic Series 70, pp 133-157. doi:10.1016/S0422-9894(04)80044-8

Harms, J.C., Southard, J.B., Spearing, D.R., Walker, R.G. (1975): Depositional environments from primary sedimentary structures and stratification sequences. Dallas, *SEPM Short Course* Nº 2, 161p.

Hayes, M.O. (1975): Morphology of sand accumulation in estuaries: an introduction to symposium. In: Cronin, L.E. (Ed.), *Estuarine Research, II, Geology and Engineering*. Academic Press, Inc., pp 3-22. doi:10.1016/B978-0-12-197502-9.50006-X

Heniche, M., Secretan, Y., Boudreau, P., Leclerc, M. (2000): A two-dimensional finite element drying-wetting shallow water model for rivers and estuaries. *Advances in Water Resources* 23, 359-72. doi:10.1016/S0309-1708(99)00031-7

Huijts, K.M., de Swart, H.E., Schramkowski, G.P., Schuttelaars, H.M. (2011): Transverse structure of tidal and residual flow and sediment concentration in estuaries. *Ocean Dynamics* 61(8), 1067-1091. doi: 10.1007/s10236-011-0414-7

Le Floch, P. (1961): Propagation de la Marée dans l'Estuaire de la Seine et en Seine Maritime. Thèse Doctorat d'État (PhD Thesis). Université de Paris.

Lesourd, S., Lesueur, P, Brun-Cottan, J.C., Auffret, J.P., Poupinet, N., Laignel, B. (2001): Morphosedimentary evolution of a macrotidal estuary subjected to human impact; the example of the Seine (France). *Estuaries* 24(6b), 940-949. doi: 10.2307/1353008

Li, M.T., Chen, Z.Y., Yin, D.W., Chen J., Wang, Z.H., Sun, Q.L. (2011): Morphodynamic characteristics of the dextral diversion of the Yangtze River mouth, China: tidal and the Coriolis Force controls. *Earth Surface Processes and Landforms* 36(5), 641-650. doi: 10.1002/esp.2082

Loriente, E. (1987): La vegetación halófila de las marismas de Cantabria. II. *Anales del Instituto de Estudios Agropecuarios* 10, 9-24.

Menier, D., Reynaud, J.Y., Proust, J.-N., Guillocheau, F., Guennoc, P., Bonnet, S., Tessier, B., Goubert, E. (2006): Basement control on shaping and infilling of valleys incised at the southern coast of Brittany, France. In: Dalrymple, R.W., Leckie, D.A., Tillman, R.W. (Eds) Incised valleys in time and space. Society of Economic Paleontologists Mineralogists Special Publication 85. pp. 37–55

Milliman, J.D. (1980): Sedimentation in Fraser River and its estuary, southwestern British Columbia, Canada. *Estuarine and Coastal Marine Science* 10, 609-633. doi:10.1016/S0302-3524(80)80092-2

Monge-Ganuzas, M., Cearreta, A., Evans, G. (2012): Morphodynamic consequences of dredging and dumping activities along the lower Oka estuary (Urdaibai Biosphere Reserve, southeastern Bay of Biscay, Spain). *Ocean and Coastal Management* 77, 40-49. doi:10.1016/j.ocecoaman.2012.02.006

MOPT (1992): Clima Marítimo en el Litoral Español. ROM 0.3-91. Oleaje. Anejo 1. Centro de Publicaciones (Ed.), Secretaría General Técnica. Ministerio de Obras Públicas y Transportes.

Morales, J.A., Sedrati, M., Cantano, M., Rodríguez Ramírez, A., Delgado, I., Lozano, C., Flor-Blanco, G. (2014): From the continent to the coast: the bedload transport across the lower sector of the Guadiana River Mouth (Spain-Portugal). *Géomorphologie* 3(3), 251-260.

Naughton, F., Sánchez Goñi, M.F., Drago, T., Conceição Freitas, M., Oliveira, A. (2007): Holocene changes in the Douro estuary (Northwestern Iberia). *Journal of Coastal Research* 23(3), 711-720. doi: 10.2112/05-0462.1

Nichols, M.M., Biggs, R.B. (1985): Estuaries, in: Davis, R.A. Springer-Verlag, J.R., (Eds), *Coastal Sedimentary Environments*, (2nd ed.), pp. 77-186. doi: 10.1007/978-1-4612-5078-4_2

Ojeda, J., Sanchez, E., Fernandez-Palacios, A., Moreira, J.M. (1995): Study of the dynamics of estuarine and coastal waters using remote sensing: the Tinto-Odiel estuary, SW Spain. *Journal of Coastal Conservation* 1, 109-118. doi: 10.1007/BF02905119

Ortiz Berenguer, F.J., Arteche García, J.L., Sanz Moral, P. (2004): Caracterización del oleaje en las aguas costeras del Cantábrico, In: García Codrón, J.C., Diego Liaño, C., Fernández de Arróyabe, Garmendia Pedraja, C., Rasilla Álvarez, D. (Eds.), *El Clima, entre el Mar y la Montaña*. Pub. Asoc. Esp. de Climatología (AEC). Servicio de Publicaciones de la Universidad de Cantabria., Serie A, 4, pp 95-104.

Pascual, A., Martínez García, B., Rodríguez Lázaro, J., Martín Rubio, M. (2009): Distribución de los Foraminíferos bentónicos recientes en el estuario de Tina Menor (Cantabria). *Geogaceta* 47, 45-48.

Perillo, G.M.E. (1995): Definitions and geomorphologic classifications of estuaries. In: Perillo, G.M.E. (Ed.), *Geomorphology and Sedimentology of Estuaries. Developments in Sedimentology*. Elsevier, Amsterdam, 53, pp. 17-47. doi:10.1016/S0070-4571(05)80022-6

Piedracoba, S., Souto, C., Gilcoto, M., Pardo, P.C. (2005): Hydrography and dynamics of the Ria de Ribadeo (NW Spain), a wave driven estuary. *Estuarine, Coastal and Shelf Science* 65, 726-738. doi:10.1016/j.ecss.2005.07.013

Portela, L. (2008): Sediment transport and morphodynamics of the Douro River estuary. *Geo-Marine Letters* 28, 77-86. doi: 10.1007/s00367-007-0091-1

Posamentier, H.W., Vail, P.R. (1988): Eustatic controls on clastic deposition II—sequence and systems tract models. In: Wilgus, C.K., Hastings, B.S., Posamentier, H.W., Van Wagoner, J., Ross, C.A., Kendall, C.G.St.C. (Eds.), *Sea-level Changes: An Integrated Approach*, vol. 42. SEPM Publication, pp. 125-154. doi: 10.2110/pec.88.01.0125

Pritchard, D.W., 1955. Estuarine circulation patterns. *Proceedings of the American Society of Civil Engineers* 81, 717-729.

Roson, G., Álvarez-Salgado, X.A., Pérez, F.F. (1997): A non stationary box model to determine residual fluxes in a partially mixed estuary, based on both thermohaline properties. Application to the Ria de Arousa (NW Spain). *Estuarine, Coastal and Shelf Science* 44, 249-262. doi:10.1006/ecss.1996.0127

Roy, P.S. (1984): New South Wales Estuaries: Their origin and evolution. In: B.G. Thom (ed.), *Coastal Geomorphology in Ausralia*. Academic Press, Sydney. pp. 241-263.

Ryan, D.A., Heap, A.D., Radke, L., Heggie, D.T. (2003): Conceptual models of Australia's estuaries and coastal waterways; application for coastal resource management. *Geoscience Australia*. Commonwealth of Australia, 145p.

Sloss, C.R., Jones, B.G., McClennen, Ch.E., de Carli, J., Price, D.M. (2006): The geomorphological evolution of a wave-dominated barrier estuary: Burrill Lake, New South Wales, Australia. *Sedimentary Geology* 187, 229-249. doi:10.1016/j.sedgeo.2005.12.029

Simmons, H.B. (1955): Some effects of upland discharges on estuarine hydraulics. *Proceedings of the American Society of Civil Engineers* 81, 1-20.

Sorrel, P., Tessier, B., Demory, F., Baltzer, A., Bouaouina, F., Proust, J.-N., Menier, D., Traini C. (2010): Sedimentary archives of the French Atlantic coast (inner Bay of Vilaine, south Brittany): Depositional history and late Holocene climatic and environmental signals. *Continental Shelf Research 30,* 1250-1266. doi:10.1016/j.csr.2010.04.004

Tessier, B. (2012): Stratigraphy of tide-dominated estuaries. In: Davis, R.A., Dalrymple, R.W. (Eds.), *Principles of Tidal Sedimentology*. Springer, London, pp. 109-128. doi: 10.1007/978-94-007-0123-6_6

Uriarte, A., Jesús Belzunce, M., Solaun, O. (2004): Characteristics of estuarine and marine sediments. *Elsevier Oceanography Series* 70, 273-282. doi:10.1016/S0422-9894(04)80049-7

Valle-Levinson, A., Wong, K.C., Lwiza, K.M.M. (2000): Fortnightly variability in the transverse dynamics of a coastal plain estuary. *Journal of Geophysical Research* 105(C2), 3413-3424. doi: 10.1029/1999JC900307

Waeles, B., Le Hir, P., Lesueur, P., Delsinne, N. (2007): Modelling sand/mud transport and morphodynamics in the Seine river mouth (France): an attempt using a process-based approach. *Hydrobiología* 588(1), 69-82. doi: 10.1007/s10750-007-0653-2

Wentworth, C.K. (1922): A scale of grade and class terms for clastic sediments. *Journal of Geology* 30, 377-392. doi: 10.1086/622910

Wright, L.D. (1977): Sediment transport and deposition at river mouths, a synthesis. *Geological Society of America Bulletin* 88, 857-868. doi: 10.1130/0016-7606(1977)88<857:STADAR>2.0.CO;2