THEMATIC ISSUE

Dynamics and sedimentary assessment of a rock-bounded estuary: a case study—Tina Mayor (NW Spain, Iberian Peninsula)

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Abstract

Based on a comprehensive study of the Tina Mayor estuary, a conceptual morphosedimentary model is proposed for one of the best-preserved limestone sectors of the Iberian Peninsula. This mesotidal and rock-bounded estuary consists of a significant proportion of quartzitic gravel fractions, which is distinctive compared to the other nearby estuaries of Northwest Spain on the Iberian Peninsula. Fluvial discharges allow for high coarse fraction inputs to be distributed to all the geomorphological estuarine zones, particularly the mouth, the bay and the inner areas. Moreover, the narrowing of the rocky boundary affects the outermost sector of the mouth of the estuary, developing two coarse grain spits; the inner being much more extensive, while tidal flats occupy a greater reclaimed area than the natural ones. The dominant sedimentary flow regime was established based on tidal and current records during a tidal cycle. The flood currents crossing the bay change trajectory at the mouth boundary as a result of rocky narrowing from the western mouth to the eastern inner side in a reverse response to the Coriolis effect. Estuarine morphosedimentary units are mapped, including the large and minor bedforms in each estuarine zone. These have been characterised according to the average values of the granulometric parameters (coarsest 1-percentile grain size or centile, mean size, sorting, skewness and kurtosis), as well as the carbonate (bioclast) percentage, including the trend maps of the mean size, sorting and biogenic carbonate content. Furthermore, taking into account the mean tidal amplitude and mixing waters (QF/QT), a suitable classification can be established for any type of estuary, including the characteristics of the confinement of the estuary mouth.

Keywords Morpho-sedimentary units · Diagram classification · Dynamic-sedimentary model · Geomorphology · Asturias–Cantabria

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Introduction

As transitional coastal zones, estuaries are of great environmental importance and are protected by a variety of environmental institutions (Ramsar Convention, Special Protection Areas—SPA, and Sites of Community Importance—SCI) and have, therefore, been studied from different points of view. Geomorphological and sedimentological studies have been published focussing on the southern Iberian Peninsula, specifically Huelva and the south coast of Portugal (Guadiana) (Borrego et al. 2013; Ruiz et al. 2013; Morales et al. 2014, 2015; Sampath and Boski 2016; Garel et al. 2019; Carro et al. 2019), as well as works examining records of tsunamis dating back to the Holocene (Morales et al. 2008; Lima et al. 2010; Costa et al. 2012). In the north, dynamics, sedimentology and geomorphology have been widely addressed such as in Vigo Ria (Perez-Arlucea et al 2005; Vilas et al. 2019).

Numerous studies have been carried out in different estuaries in the north of Spain, demonstrating the effect of the Coriolis gyre and its influence on the distribution of water mixtures, sediment distribution and morphologies in Vigo (Ruiz-Villarreal et al. 2002; Piedracoba et al. 2005), Eo (Flor et al. 1992), Villaviciosa (Flor et al. 2015) and the neighbouring Tina Menor (Flor-Blanco et al. 2015a) and San Vicente de la Barquera (Flor-Blanco et al. 2015b), as well as studies of the effects of anthropegenic environmental changes resulting from jetties (Flor-Blanco et al. 2015c) and dredging (Flor-Blanco et al. 2013; Monge-Ganuzas et al. 2019).

On the other hand, geochemical contamination due to industry and mining is present in studies from the south, following pollution in the Tinto River (Nieto et al. 2007; González-Ortegón et al. 2019; Cánovas et al. 2020), while in northern Spain, research in Galicia in Vigo (Rubio et al. 2000) and Ferrol (Álvarez-Vázquez et al. 2020), and Asturias in the Nalón, as well as in the Villaviciosa and Llanes estuaries (García-Ordiales et al. 2018, 2020a) are noteworthy.In our study area, however, the human footprint has not been as

pronounced as in the aforementioned estuaries, maintaining a mostly intact rock-bounded morphology, but with a low degree of anthropisation, except in the marshes, and a high fluvial influence from the dynamic and sedimentary point of view.

The Cantabrian coast (Bay of Biscay, northern Spain) is home to many filled estuaries, sometimes referred to as *rias* (Castaign and Guilcher 1995; Evans and Prego 2003). These are former fluvial valleys developed in a high relief, coastal area (Fig. 1). In this case, the sedimentary fill of the estuary of Tina Mayor, with a length of 5.15 km, occupies an old narrow, carved valley of the Deva River, which extends by a sand strip which is on average 100 m wide and slightly sinuous on the inner continental shelf. Some of these estuaries are linked to rivers rooted in the watershed of the Cantabrian Range, such as the estuary of Ribadesalla (Asturias), and its confining barrier is constituted by sand (exposed beach and removed aeolian dune field). Gravel fractions form a minority on the beach, while gravel is more prevalent in the estuarine
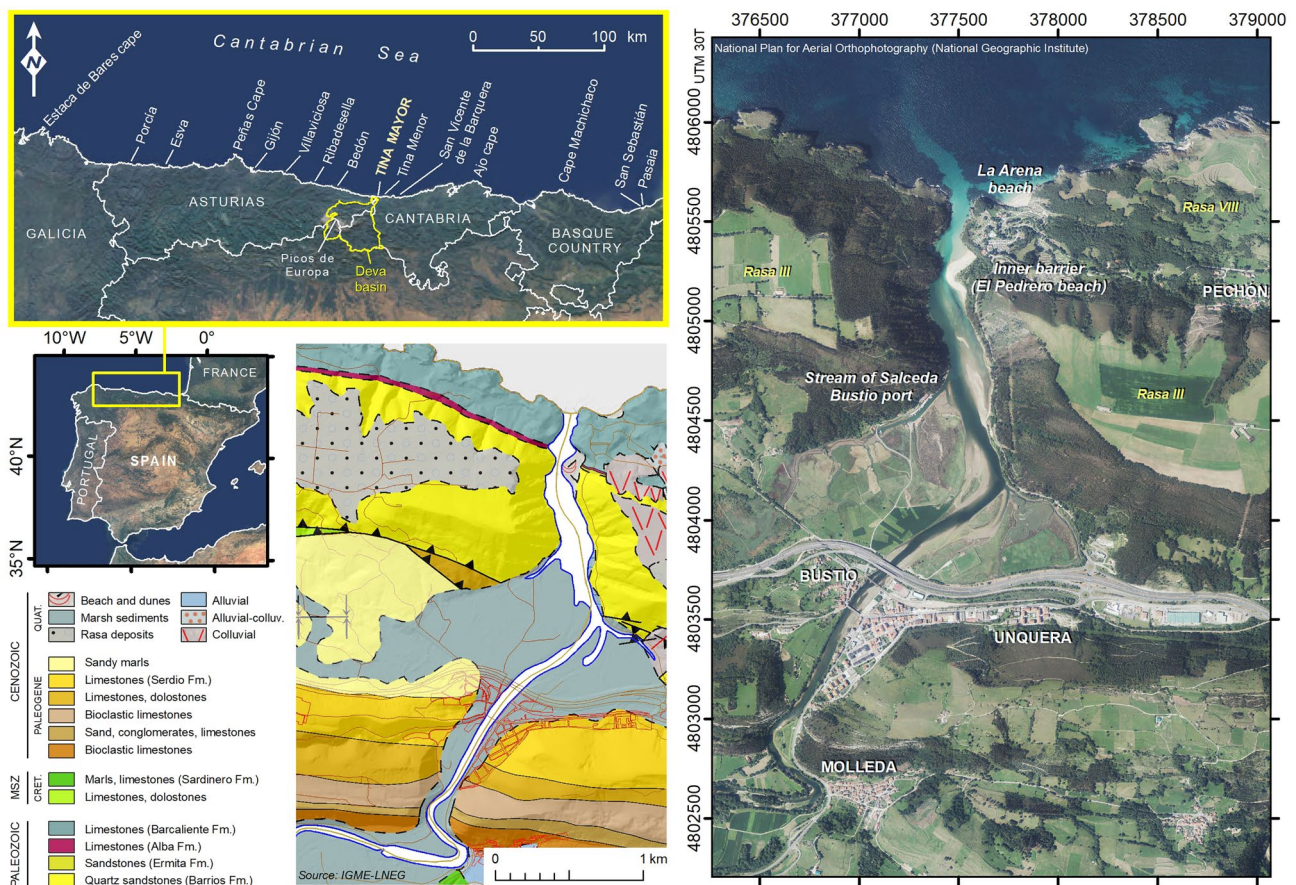

Fig. 1 Location of the estuary of Tina Mayor (Asturias–Cantabria) in the NW Spanish littoral (Iberian Peninsula) in the Cantabrian Sea (S Gulf of Biscay). The bottom sands in the outer estuary are part of the submerged coastal prism that extends along the submerged paleo-

valley and towards the E, where the pocket beach of Las Arenas is developed. Other mentioned estuaries are included as well as the old estuary of Gijón-Piles (bold italics)

zones of the bay and the upper channel (Flor-Blanco and Flor 2019).

It is worth noting that few studies have been carried out in estuaries filled mostly with gravel sediments, in part because they are more scarce than those filled by sand and mud. In most estuaries it is assumed that the landward zone (upstream) is dominated by riverine sedimentation constituted by gravel, gravelly sand and sandy gravel, but not in the outermost sector. In the north of Europe, sediments of glacial origin are coarse (gravel and cobbles) and reworked by wave action (Cooper 2004). Moreover, gravel barriers are most often studied on glaciated coasts with heterogeneous sediments that were actively sorted by waves (Orford et al. 1996). There are few estuaries which export coarse-grained sediments to the nearshore such as in northern New England (Fitzgerald et al. 2005). For example, at the mouth of the Senna estuary (France), coarse fractions of sands and gravels predominated until they were replaced by silts and fine sands in recent decades as a result of anthropogenic activity (Lesourd et al. 2016).

The Rio Grande estuary (Tierra del Fuego, Argentina) does have certain similarities to Tina Mayor in terms of the inlet morphology which varies in relation to longshore-drift, wave-refraction and ebb-tidal delta accumulation phases and an increasing in the urbanisation of the saltmarshes (Isla and Bujalesky 2004). With regard to Spain, the only investigation of dyamics and sedimentation in the Stella estuary (Asturias) was published by Flor and Camblor (1989) with equivalences to Tina Mayor in dynamics and sedimentary fractions.

Other draining rivers with these characteristics are coastal, such as the estuary of Porcía, located in the western Asturias and the intermediate rivers of Bedón and Esva in eastern Asturias (Flor and Flor-Blanco 2014), and in the western areas, respectively. In these cases, their confining barriers are constituted by gravel and some sand and are not completely developed in relation to tidal dynamics and sedimentary distribution, so that only a small surface is flooded during tides and about 4.30 h in spring tides, as studied by Villegas et al. (1992) in the Esva estuary (Fig. 1).

The aim of this paper is to present a complete and comprehensive study of this type of estuary with a predominance of gravel fractions, which is under-represented in the Iberian Peninsula and for which scientific studies are scarce. The purpose is to examine the dynamics, sedimentation and morphology of a highly confined estuary which has not been modified by human activity in its external sector, except for the normal use of marshes for agriculture and shipping.

To determine the reasons for the singular disposition of some of the estuarine units, a morphodynamic and sedimentary model is proposed. This model includes the complete set of active variables in the most representative subenvironments. Moreover, combining mixed patterns and mouth morphology, a new type of classification is presented that combines more classifications published by other authors, which can be extrapolated to all types of estuaries.

Regional setting

In the north of Spain, alternating with the cliffs, sandy, pebble or mixed beaches, more than 50 estuaries of various sizes have developed (Flor-Blanco and Flor 2019), some are controlled by the rock substrate and are classified as rock-bounded estuaries.

The Cantabrian coast displays a clear and well-defined, latitudinal W–E alignment and is characterised by cliffs of differing heights, with up to 12 levels of flat erosion surfaces called rasas (Flor and Flor-Blanco 2014; Dominguez-Cuesta et al. 2015), highlighting a continuous unique surface with an average height of 100–150 m (López-Fernández et al. 2020). This is related to the previous Variscan structures and the alpine tectonic accidents. From the Miocene period to the present, intermittent elevation allowed for the formation of these rasas. The upper levels are developed in the quartzitic range of Pechón on the eastern side (>200 m) and a lower erosion surface (rasa VIII of 61–63 m) eroded the carboniferous limestone (Fig. 1), as well as the two lower rasas (XI $=7$–9 m and XII $=4$ m). The latter is only preserved on the eastern bank of the estuary, being the same height as the active notch. The latter is only preserved on the eastern shore of the estuary, being at the same height as the active notch, i.e. in the intertidal of La Arena beach.

The estuary of Tina Mayor forms a natural boundary between the provinces of Cantabria and Asturias in northern Spain (Iberian Peninsula, Cantabrian Sea) (Fig. 1). According to Beck et al. (2018) and based on the Köppen–Geiger classification (Köppen 1936), this northern temperate and humid region corresponds to a Cfb climate. The southern area is occupied by the W–E-trending Cantabrian Range as the westward extension of the Pyrenees. The northern catchments of Spain are steep and narrow, and short valleys carved by rivers flow towards the coast (Jiménez-Sánchez et al. 2014).

The estuary was filled on the old excavated, narrow valley of the Deva River. This river and the tributary Cares have lengths of 50.23 km and 53.48 km, respectively (Flor-Blanco and Flor 2019). Its basins are excavated on the Picos de Europa unit (Heredia et al. 2003), mainly calcareous, but both headwaters are developed on shales and sandstone with a surface area of 1194 km^2 (Deva: 643.91 km^2 and Cares: 494.75 km^2) and a total perimeter of 184.30 km, with an average height of 1013 m. The average slope is 50.36% in the Picos de Europa unit (Heredia et al. 2003) and only 29% in the lower reaches of the Deva and Cares up to the mouth (GESHA 2004).

The lower courses of the Deva and Cares Rivers and the inner estuary of Tina Mayor cut the sedimentary rocks, which are constituted by siliciclastic materials of sand, silt and marls, including limestone and dolomites from the Cretaceous period and Lower Tertiary marine. The major lithostratigraphic units outcropping in the outer estuary are the Barrios Quartzite (Ordovician), Barcaliente, Valdeteja, Cuera, Picos de Europa and Beleño formations, all Carboniferous in age. Vertical Variscan thrusts and faults have a W–E trend in the eastern and western parts of Asturias and Cantabria, respectively. The Paleozoic rocks overthrust the mesotertiary sedimentary succession (Portero García et al. 1976; Martínez 1980).

The trace of the river has a perpendicular arrangement regarding the tectonic structure in a north–south direction in which materials are embedded. The stratification is only conformable in very small segments, more often in a W–E direction, due to the most erodible material aligned W–E of the Upper Tertiary (marls, marly limestone and sand). Moreover, the broad tidal flats aligned W–E were excavated on the nucleus of a Tertiary syncline W–E of the sandy marls dating back to the Middle Paleocene (Portero García et al. 1976; Martínez 1980). This is indicative of the strong influence exerted by a relatively broad fluvial catchment of the two rivers, anchored in the watershed of the Cantabrian Range, showing a great capacity for erosion and transport due to the aforementioned steepness of 29.0%.

Dynamic agents

The Cantabrian coast is considered a high-energy environment with strong and persistent winds from various directions when the Azores High System affects the Iberian Peninsula (Flor-Blanco et al. 2015a, b). Data collected from SIMAR point 3,122,034 (4.42º W–43.42º N) indicates that between 1958 and 2020 (Puertos del Estado), predominant wave direction came from the NNW (42.19%), NW (36.43%) and, less frequently from the N (10.28%), while the most frequent wave heights vary between 0.5 and 1 m. Mean significant wave height, Hs, of 1 m and a typical winter storm wave of Hs 5 m. The peak period higher than 9.0 s in most cases with a frequency of 65% (Aranda et al. 2020a) and recent studies highlight the recurrence of storms of Hs > 7 m between 1998 and 2015 (Flor-Blanco et al. 2021).

The Cantabrian coast is an open coastline exposed to a large fetch where the swell comes mainly from the NW (37%), WNW (29%) and, less frequently the NE (16%), often under anticyclone weather conditions. In winter, the average parameters are 2 m and 7 s, although waves of more than 9 m and 16 s have been measured. In summer, the significant height varies between 0.5 and 1 m, and the period measures between 4 and 6 s. Very strong waves usually occur in winter,

with heights of more than 6–7 m and for long periods of more than 8 s (Puertos del Estado).

One of the most important environmental agents are the tides (mesotidal and semidiurnal) with ranges between less than 1 m and 4.75 m, with an average of 2.84 m (Flor-Blanco et al. 2015a). From 1995 until 2020, the average tidal range was 2.79 m, with a historical maximum value of 5.40 m, and a minimum of 0.18 m (visited April 15, 2021. Puertos del Estado). According to the criteria of Le Floch (1961), who combines the balance of the convergence and the frictional effect, it is a hyposynchronous estuary, dissipating gradual tidal wave upstream.

The Cantabrian Range plunges abruptly into the sea in a straight line of less than 40 km. In this wet part of Spain, the rivers have short courses and the hydrological regime is dominantly nivo-pluvial until the confluence of the Deva and Cares Rivers, and from there they are pluvial in nature. Runoffs range between flood conditions (fall and spring) and dry seasons (summer). The annual regime is fairly regular with a lower coefficient of irregularity of 3, and the average specific flow varies between 377.95 L/s/km^2 and 2.54 L/s/km^2 when they come together (Fernández 1981). They flow in gorges and deep, steep-sided valleys that are highly erosive and basically of the same bedrock or boulder channel character (Raven et al. 2009).

The Deva and Cares Rivers have a similar runoff, with the upper boundary watershed in the calcareous Picos de Europa Massif (Fig. 1) being somewhat higher than the river tributary with an annual average flow of 14.39 m^3/s and 20.45 m^3/s, respectively. The rainfall per year is 1174.60 mm and the average annual discharge and water contribution is 908.49 Hm^3 or 770.92 mm, while the maximum annual runoff is 482.0 m^3/s and the minimum 0.24 m^3/s.

Materials and methods

Mapping the morphosedimentary and dynamic units and of the main bedforms was carried out on the basis of numerous field trips to the estuary since 2003, taking advantage of the spring low tides, since the morphologies can be mapped directly thanks to tidal ranges of more than 4 m. The historical evolution of the estuary and field mapping were elaborated from topographic maps, MDS LiDAR 2018–2019 (Cartographic Service of Cantabria) and a 1:5000 Cantabrian DEM (2010), with a resolution of 5 m, and the orthophotographs from 2007, 2010, 2015 and 2017 (Central Government—PNOA Plan). Six vertical aerial photos were consulted to ascertain the historical evolution and develop the dynamo-sedimentary conceptual model since 1945 and 1956 (Army Map Service, USA) and five orthophotos made by the Autonomous Communities of Cantabria and Asturias

throughout the twenty-first century were studied, as well as those from Google Earth and Bing Maps satellite images.

Data on fluvial discharges from the Deva River were obtained from the Comisaría de Aguas del Norte de España (Ministerio de Fomento) and used to calculate the volumes of fresh water introduced to the estuary during dry and flood runoffs. Many of these records date back to 1940 and some of these measuring stations were located near the mouth of the river, though no such stations exist today.

Furthermore, the saltwater volumes during neap and spring tides (a maximum range of 1.0–4.5 m respectively),

were calculated. According to some authors' criteria (Pritchard 1956; Cameron and Pritchard 1963), four possible results of mixed waters were estimated.

Data regarding salinity, direction, and velocities of the currents were simultaneously obtained on a boat by fixing eight transverse profiles to the estuarine axis from the mouth to the inner estuary, along a spring tidal cycle and low river discharge, excluding low tides (Fig. 2). For the currents, a General Oceanics electronic flowmeter (Model 2035-MK III) and Global Water 800-876-1172 (Model FP101) were used and a handheld multiparameter

Fig. 2 Location of the measuring points of tidal rangesand, in the entire water column, salinity and direction and velocity of currents obtained on a boat, and bottom samples to characterise the sediments. Limits of saline and tidal intrusions are located
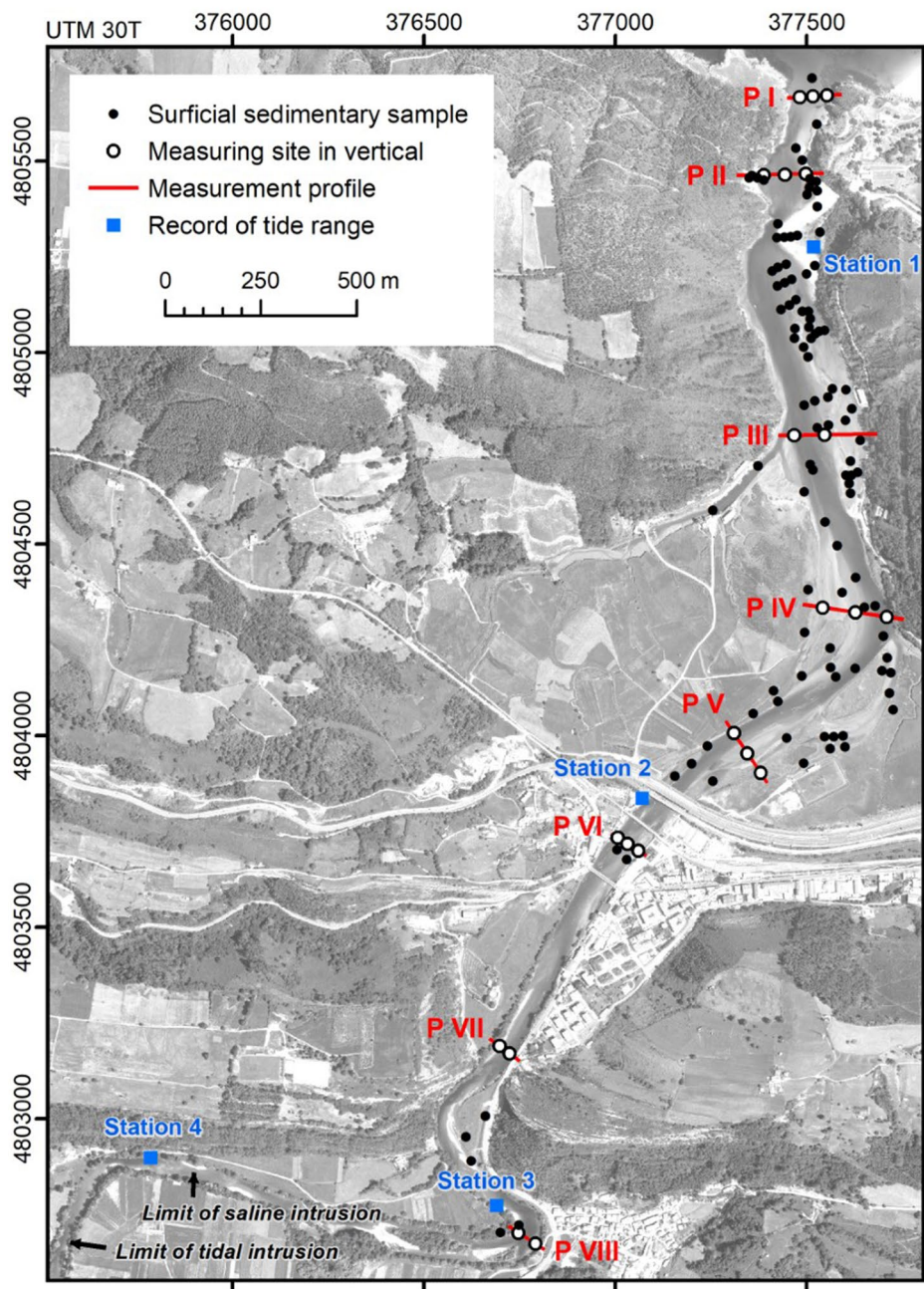
instrument (YSI 556 MPS) recorded the salinity. Each data measure in the water column was acquired every 0.5 m (Fig. 2). Saline distribution on the surface is useful when deducing the water mixture trends relating to the main ebb and flow currents. On the other hand, the circulation scheme was obtained by recording the velocity and the direction of the currents, as well as the saline distribution through the whole water column at a 0.5 m interval in depth, being operative up to a maximum depth of 4.50 m during another tidal cycle.

Four fixed stations recorded the ranges of the tidal wave in a tidal cycle to determine the dissipation upstream of this stationary wave (Fig. 2). Measurements were taken with a graduated scale in millimetres, positioned vertically over a spring tidal cycle and low river discharges at 10-min intervals, and simultaneously for positioning the upper limit of the stationary wave during a spring tide and medium–high fluvial runoff, since they are the prevailing seasonal conditions. Inner saline and mechanical tidal waves were established during low fluvial discharge and spring tides.

Surficial and unconsolidated, representative, sedimentary samples of the active and other natural bottoms (116), mainly of gravel, sand and mixed sediments, as well as mud flats, were taken during spring low tides. To provide better information on the carbonate content, sands were sampled in sandy areas and in the sand surrounding the gravel deposits.

The samples of the submerged bottoms deeper than 1.5 m were collected with a Petersen-type grab sampler mounted on a boat (Fig. 2), and the location was recorded using a Garmin GPS unit. The samples were washed, dried at 35 °C and analysed to obtain the grain size distribution (textural parameters), using CISA sieves in up to eleven different sizes (ISO-3310.1), namely 1.41 mm, 1 mm, 710 μm, 500 μm, 355 μ, 250 μm, 180 μm, 125 μm, 90 μm, 63 μm y 45 μm.

The textural parameters were obtained according to Folk and Ward's method (1957) and GRADISTAT software (Blott and Pye 2001). To complete the sedimentological information, the intertidal bedforms were directly measured and photographed during low tide periods to deduce the local currents that generate them.

All data and information were processed in a GIS, moreover, figures were also generated using other graphic editing programmes.

The data obtained have provided a complete knowledge of the dynamics, sedimentation and geomorphology of this estuary, allowing us to identify the state of the estuary at each tidal moment and for different scenarios varying from higher to lower water flow. All this is integrated in the proposed triangular classification that includes the water mixtures (QF/QT) and the tide ranges, which can be extrapolated to all types of estuaries.

Results

Estuarine geomorphology

From a geomorphological point of view, the estuary can be segmented into four zones from the mouth to the inner tide limit, the mouth complex, bay, tidal flats and upper channel (Flor 1992), and some basic data such as length, width and the occupied surface has been calculated (Fig. 3).

The particular characteristic of this estuary is the lack of an outer submerged sand prism, linking to the inner continental shelf. It has only produced a sedimentary infill of the previous excavated fluvial valley according to a narrow belt bordered by a rocky bottom (Figs. 3, 4A). The mouth complex is confined mainly by rocky margins, developing two sets of confining spits or barriers. The outer is incipient and the inner barrier, which is broader, is constituted by an emerged, consolidated spit. Between both barriers, a small, open bay includes an exposed, embayed beach and a spill-over lobe, both made of gravel (Fig. 3).

The estuarine bay is narrow and elongated, with a higher proportion of quartzitic gravel and sands. The main channel is located on the western side and the eastern area contains a variety of bars, estuarine beaches and large emerged lobes, some of which are superimposed with numerous bedforms, including gravel and pebbles in 2D and 3D morphologies, gravel longitudinal lobes and scours. A very narrow belt of mud flats has stabilised along the western river bank in this bay due to the shadow effect of the western promontory (Fig. 3).

These outer estuarine zones have changed a great deal during the second half of the twentieth century and the last twenty years, especially the bar complexes in the bay, as these can be analysed through historical aerial photographs, orthophotos and field photographs. However, tidal mud flats comprise the largest area and many gravely and sandy fluvio-tidal flats with fluvial control have been reclaimed by humans for various uses, mainly grazing, cultivation and the construction of the Bustio port and its access roads (Fig. 3). The active inner estuary is restricted to the main channel and associated gravel bars, as are the point bars and lateral and central bars, as well as some sand sheets generated by sporadic overflows.

The tidal flat zone is best represented (57.70%), followed by the upper channel (34.32%) and bay (5.68%), and a minimum of 2.30% in the case of the mouth complex (Table 1).

Mouth complex

Rey Salgado and Sanz Alonso (1981) carried out research in the outer mouth of the estuary to determine the
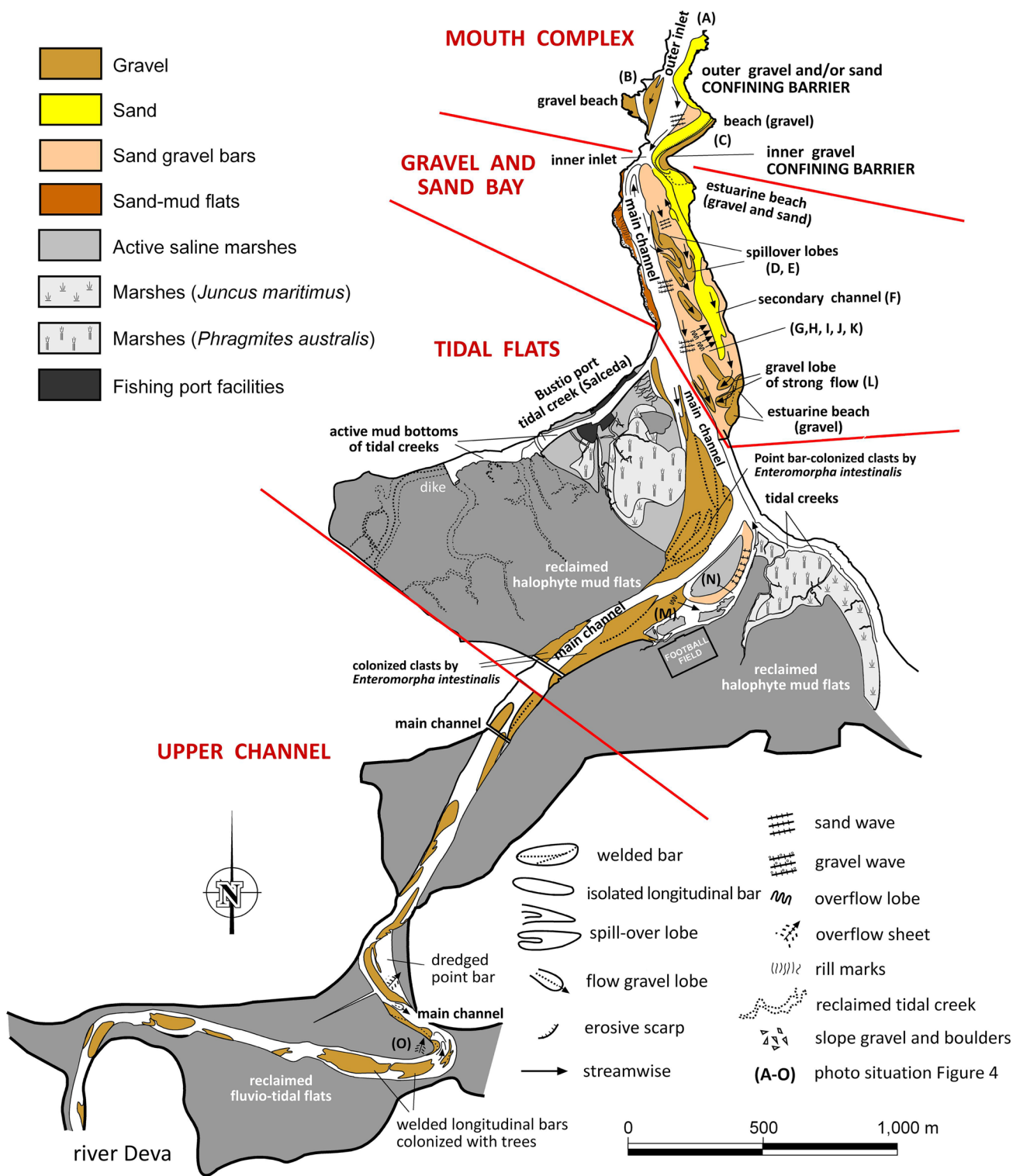
Fig. 3 Geomorphological zonation of the estuary of Tina Mayor, differentiating the main morphosedimentary units, large bedforms and other structures, and main vegetal colonisation. Arrows show the direction of flow downcurrent generating some of those structures

◀**Fig. 4 A** An aerial photo from 2017 of the lower estuary and the transition to the inner continental shelf. **B** The embayed gravel beach of El Puertín in the background and gravel elongated spill-over lobe. **C** Inner gravel barrier and inlet. **D** and **E** Flat topped gravel welded bars. **F** Broad spill-over lobe with a sandy ramp. **G** Small gravel lobes migrating on the sand secondary channel. H) Detail of previous photo. **I** Large scours in the right side of the main channel a transverse gravel wave. **J** Flat gravel sheet migrating to the right. **K** Small gravel waves and incipient scour partially colonised by the green algae Enteromorpha intestinalis. **L** Large gravel lobe growing to the left side perpendicular to the main channel. **M** Large gravel current crescent during ebb tide on the right side of the main channel. **N** Lateral channel developing sand waves during ebb tides. **O** Sand overflood sheet culminated with current ripples

morphological and sedimentary transition to the inner continental shelf. The results show how the excavated river palaeo valley was filled by sandy sediments, as verified by aerial photographs, i.e. in 2017 (Fig. 4A). The narrow sedimentary prism continues to the SE as a part of the embayed sand on the neighbouring eastern beach.

The lower estuary is confined to a straight narrow NNE–SSW corridor of 200 m and an average width of 90 m that is limited by calcareous cliffs and a permanently submerged sandy bottom. On the east side, an incipient gravel and pebble confining barrier and another inner gravel barrier have developed 215 m apart, and are stabilised by the same margin (Figs. 3, 4A). These are subject to morphological control by the rocky narrowing, so that the sediments can be distributed according to the different sedimentary and morphological units (Table 2). The western margin is characterised by a embayed, gravel beach, and a gravel spill-over lobe (Fig. 4B) (maximum 125 m long) and a relatively broad, flat bottom that links to the inner barrier spit oriented NE–SW (Figs. 3, 4C). The inner spit still preserves the remains of a vegetated tabular dune.

One of the peculiarities of this estuary is that due to its rocky narrowing, there are two inlets, an outer and an inner (Figs. 3, 4A). These are the most energetic units of the entire estuary through which the entire volume of incoming and outgoing water and sediments is channelled. This exchange channel is constituted by a depressed bed located on the western margins of this, mostly outer, segment (Fig. 3).

From the distribution of the spill-over lobe, attached to the western margin of the inlet, (Fig. 4B), a deduction can be made that strong currents are generated during half rising tides, while at high tides, refracted waves have an affect on the adjacent beach (Fig. 4B). Nevertheless, during river flooding and wave storms, the outer sand barrier can be completely removed and this outer segment acts as a broad exchange channel.

The inner gravel barrier (Figs. 3, 4C) contains supratidal berms that are arranged concentrically. This large barrier structure is generated by a prograding process which is

deduced from the disposition of the vegetation in vertical aerial photos. Moreover, the southern limit of the gravel and sand bay is obliquely NW–SE, due to the strong inflow during half rising tides, the position of the inner inlet and the rocky confinement (Fig. 3).

Gravel and sand bay

This estuarine zone is flanked by the slopes of the carved valley displaying a regular plan, aligned NNW–SSE along more than one kilometre and an average width of 250 m (Fig. 3). According to this trend, four morphological and sedimentary belts (Table 2) are generated from the west to east side.

1. A narrow strip of mud flats in a sheltered area.
2. The main channel of gravel flatbed has a N–S distribution.
3. A broad complex of simple and welded gravel bars, 75 m wide and 1073.5 m long (Fig. 4D), where gravel spill-over lobes with sand ramps (Fig. 4H) are the most characteristic morphosedimentary and dynamic units, longitudinal gravel bars flat morphology on top (Fig. 4D, E), the at times badly defined contours are slightly oblique (NW–SE). At the edge of the main channel, several sedimentary structures have formed due to strong currents transversing and scouring (Fig. 4F) gravel bedforms (Fig. 4H) and small gravel lobes (Fig. 4K, L). This morphosedimentary unit has undergone remarkable yearly changes and over the long term, as can be seen in all historical aerial photographs since 1945.
4. A narrow, sandy depression of 795 m, here considered a secondary channel, begins in the estuarine beach on the outer barrier, widening towards the south (from 25 to 73.5 m). Many straight current and oscillation ripples cut crest ripples, as well as bioturbation by *Scrobicularia plana*, trails of *Peringia ulvae*, simple and some U-shaped burrows of polychaete worms and feeding accumulations by *Arenicola marina* and *Nereis diversicolor*. This area is contoured by gravel sediments developing estuarine gravel beaches on the eastern perimeter, gravel bars and a gravel lobe growing from east to west. The southeastern corner of this bay is represented by an estuarine gravel beach and gravel lobes (Fig. 4G).

Tidal flats

The main channel crosses this estuarine zone, which is the broadest, and comprises mostly reclaimed marshes (Fig. 3; Table 2). Along the northern area, the main channel forms a bend with flat bottoms and lateral welded bars, being a point bar. Upstream it has a rectilinear layout with gravel longitudinal bars in both banks. The many quartzitic clasts in both

Table 1 Geomorphological zonation of the estuary of Tina Mayor in relation to the occupied area, the length measured along the main channel and inlets as well as maximum and minimum widths

Length (m)	Width (m)%		Surface ($\times 10^5$ m^2)	%
	Maximum	Minimum		
Mouth complex				
432.5	255.0	75.0	0.55	2.40
Bay				
816.5	195.0	145.0	1.36	5.68
Tidal flats				
1190.0	1167.0	–	13.82	57.70
Upper channel				
2871.0	397.8	62.96	8.22	34.42

bars are covered by a sheet of the green algae *Enteromorpha intestinalis*.

During floods, the strong current often carries tree trunks and other large items of debris, which, in some cases become permanently anchored in the banks on the right side of the river, developing gravel current crescent structures, mainly during ebb tide (Fig. 4M).

On the eastern side is an island that is a residual marsh, drained on the southern side by a wide sand channel with sand waves (Figs. 3, 4N), better activated during ebb tides. On the other hand, the inner active areas are occupied by mud flats or marshes of *Phragmites australis* and *Juncus maritimus*, and other minor vegetal species, but the reclaimed marshes are in the majority, drained by tidal creeks, and most of them have active mud bottoms (Fig. 3). Some may have been potentially recovered.
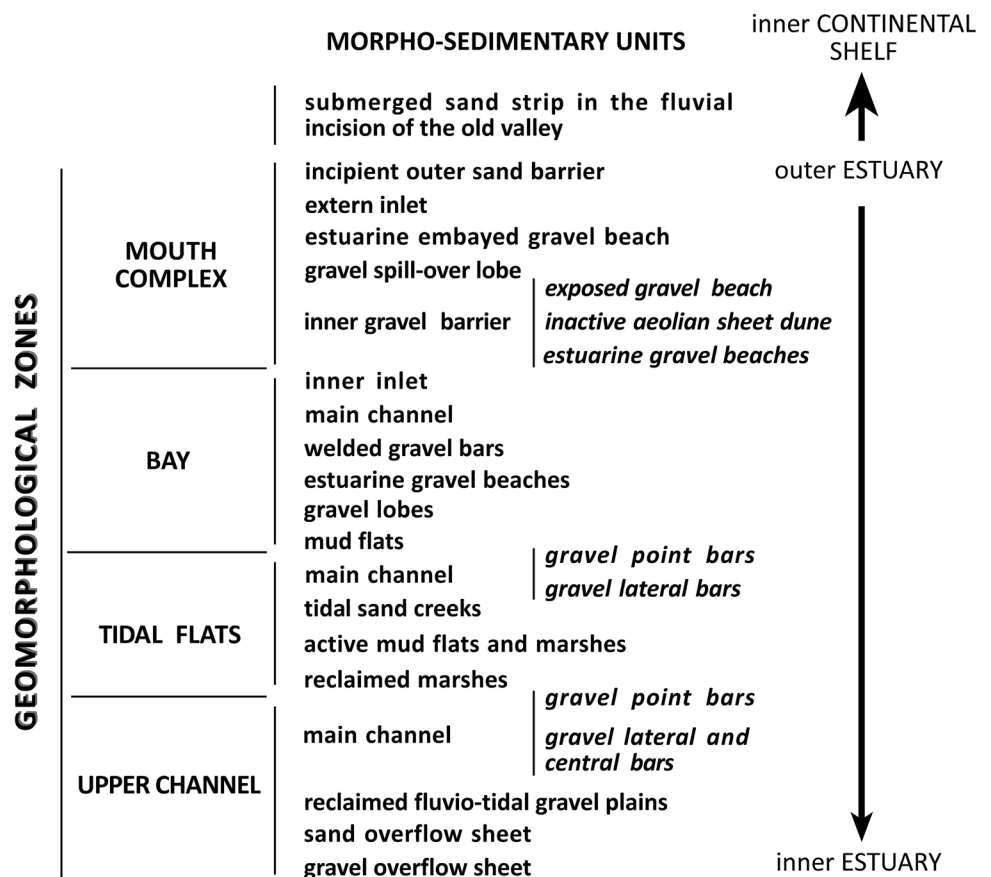
Marshes are widely drained by tidal creeks, generally with mud bottoms and vertical walls, which are very sinuous and narrow. The northern tidal channel is the largest active one where the Bustio fishing port was constructed in both margins. Maintenance dredging has triggered a sand intrusion from the main channel.

Upper channel

This estuarine geomorphological zone is the simplest, where the main channel is the most energetic unit, similar to the bay. It develops two wide gravel point bars, several lateral bars and a set of welded bars in the middle of the main channel (Fig. 3). This estuarine stretch is subject to extensive changes, depending on the fluctuations in river discharges, including the natural bar fixing with vegetation.

The fluvio-tidal plains are very broadly constituted by sands and gravel, imperceptibly linked with the river

Table 2 Large estuarine zones and the most important morphosedimentary units

MORPHO-SEDIMENTARY UNITS

GEOMORPHOLOGICAL ZONES

MOUTH COMPLEX
- submerged sand strip in the fluvial incision of the old valley
- incipient outer sand barrier
- extern inlet
- estuarine embayed gravel beach
- gravel spill-over lobe
- inner gravel barrier
  - *exposed gravel beach*
  - *inactive aeolian sheet dune*
  - *estuarine gravel beaches*

BAY
- inner inlet
- main channel
- welded gravel bars
- estuarine gravel beaches
- gravel lobes
- mud flats

TIDAL FLATS
- main channel
  - *gravel point bars*
  - *gravel lateral bars*
- tidal sand creeks
- active mud flats and marshes
- reclaimed marshes

UPPER CHANNEL
- main channel
  - *gravel point bars*
  - *gravel lateral and central bars*
- reclaimed fluvio-tidal gravel plains
- sand overflow sheet
- gravel overflow sheet

inner CONTINENTAL SHELF

outer ESTUARY

inner ESTUARY

floodplains of the main channel and two lateral streams that represent the old tidal flats. The banks of the transition area between the fluvial and tidal range are in an active phase of lateral erosion due to river floods. In relation to these high-energy events, the overflow sheets of sand or gravel are frequently generated on the nearest fluvio-tidal flats of the main channel (Fig. 4O) and the tidal creeks are poorly preserved due to anthropisation.

Sedimentological distribution

There are different proportions of the main sedimentary fractions, namely pebbles, gravel, sand and mud. The sediment gradient from the mouth to the head of the estuary ranges from coarse to extremely fine in tidal flats. However, this is only true until the upper channel zone, where the fluvial discharge is affected by incoming tidal waves and the average size increases, to even the coarsest of the estuary. These are widely represented in the upper channel due to the influence of river discharges of the bedload, constituted by pebbles, gravel and to a lesser extent, sand (Fig. 5A).

The statistical parameters of the coarsest centile (coarsest 1-percentile grain size), the mean, sorting, skewness and kurtosis are considered with their average values in each zone and their most representative morphosedimentary units (Table 3). Gramulometry parameters mapping trends, the mean size, sorting, and carbonate percentage were analysed for their contrasting features, allowing for a better comparison (Fig. 5B, C). The narrowness of this estuary makes it difficult to interpret the transitions, but the treatment of the average data by the morphosedimentary units and areas is particularly useful.

The coarsest 1-percentile grain size (centile—C) is the one percent by weight of the sample, calculated from the cumulative probability curve. In a statistical distribution, it represents the coarser sizes (maximum kinetic energy), and has been considered in the treatment of the surficial samples to compare with the other parameters, particularly the mean size and bioclastic carbonate contents. It is particularly useful because it has more contrasting values when compared with the main size. Biogenic carbonates have provided data regarding the average percent and energy (Flor 1977) in the sand fraction only. Generally, the higher the carbonate content, the greater the mean grain size and the percentile. In this study area, the highest values in discharges generated directly by the river are concentrated in the gravel bars of the upper channel. Flood and ebb-tidal currents are responsible for another set of maximum values in the bay where varied bars are generated. Moreover, the beach barrier and embayed exposed beach exhibit the same characteristics. The tidal flats develop a contrasting duality between the units linked to the main channel and the others as mud flats. This is the same trend in relation to the mean size (Fig. 5B) that is a measure of the average energy of the deposition and reveals the changes along the axis of the estuary, as well as laterally. The main channel, which is one of the most energetic units, contains coarser fractions, decreasing to the banks and tidal flats (Fig. 5A). Also, the barrier, bars and lobes, and estuarine beaches are built with gravel fractions.

The bottom sands around the outer bar vary between coarse and fine fractions (0.0–2.75 φ). The sand on the eastern side of the bay has average mean sizes of 2.0–2.75 φ (fine sands) and very fine sands, 3.25 φ in the proximity of the marshes with *Phragmites* and *Juncus*. The point bars of the main channel, developed in the tidal flat zone, have mean sizes coarser than − 6.0 φ (cobbles), and between − 5.0 and − 6.0 φ in the southern bars of the bay and inner barrier, and the left lateral bars in the tidal flats.

The coarsest fractions lie in both the bars of the bay and in the right margins of the main channel in the tidal flats area. Moreover, in the outer embayed beach in the mouth, the minimum mean size is − 4.5 φ (pebbles). The fluvio-tidal bars are nourished by flood discharges, and the mean sizes vary between − 6.0 φ (pebbles), − 2.0 φ and lower (granules), containing scarce sand fractions, some of which are included in the point bars and as overflow sand sheets (medium to fine sands). It is clear that the mud flats exhibit the finest sizes (4.17–4.41 φ) with averages of coarse silts (Table 3).

In the case of sorting parameter, the values in the mouth complex are good in: inlet (0.48 φ), sand outer barrier (0.51 φ), and the gravel inner barrier (0.47 φ). These are the best sorted in the entire estuary where energetic agents are the most active and selective (Fig. 5, Table 3). The gravel sediments have the lowest score in the complex bars and the main channel of the bay, very poorly (2.0–4.0 φ), and poorly sorted in upper stream bars and the main channel (1.26–1.57 φ), except in the inner bars (average of 2.78 φ). Gravel estuarine beaches are both well-classified (0.47 φ and 0.23 φ) and poorly sorted (1.08 φ), depending more on ebb currents than on inner waves.

On the other hand, the sands are well sorted in the aeolian inactive dune (0.44 φ) and the overflow sand sheet (0.54 φ), but poorly sorted in the tidal creeks with 2.09 φ (very poorly). In the muds, the scores are bad (1.07 φ), increasingly worse in the tidal flats (0.74 φ) and the tidal creek bottoms (1.48–1.66 φ), and the worst with 2.41 φ in the other flats.

The dominant negative skewness appears in the exposed gravel beach of the barrier (− 0.17), reworked by incoming waves while the embayed gravel beach is positive (0.26) by the strong flood currents. The gravel bars and southern estuarine beach in the bay are also negatively skewed. This can be attributed to the winnowing of fine material by the currents and waves only in the outer area and occasionally to erosion or non-deposition, as well as the addition of coarse materials.
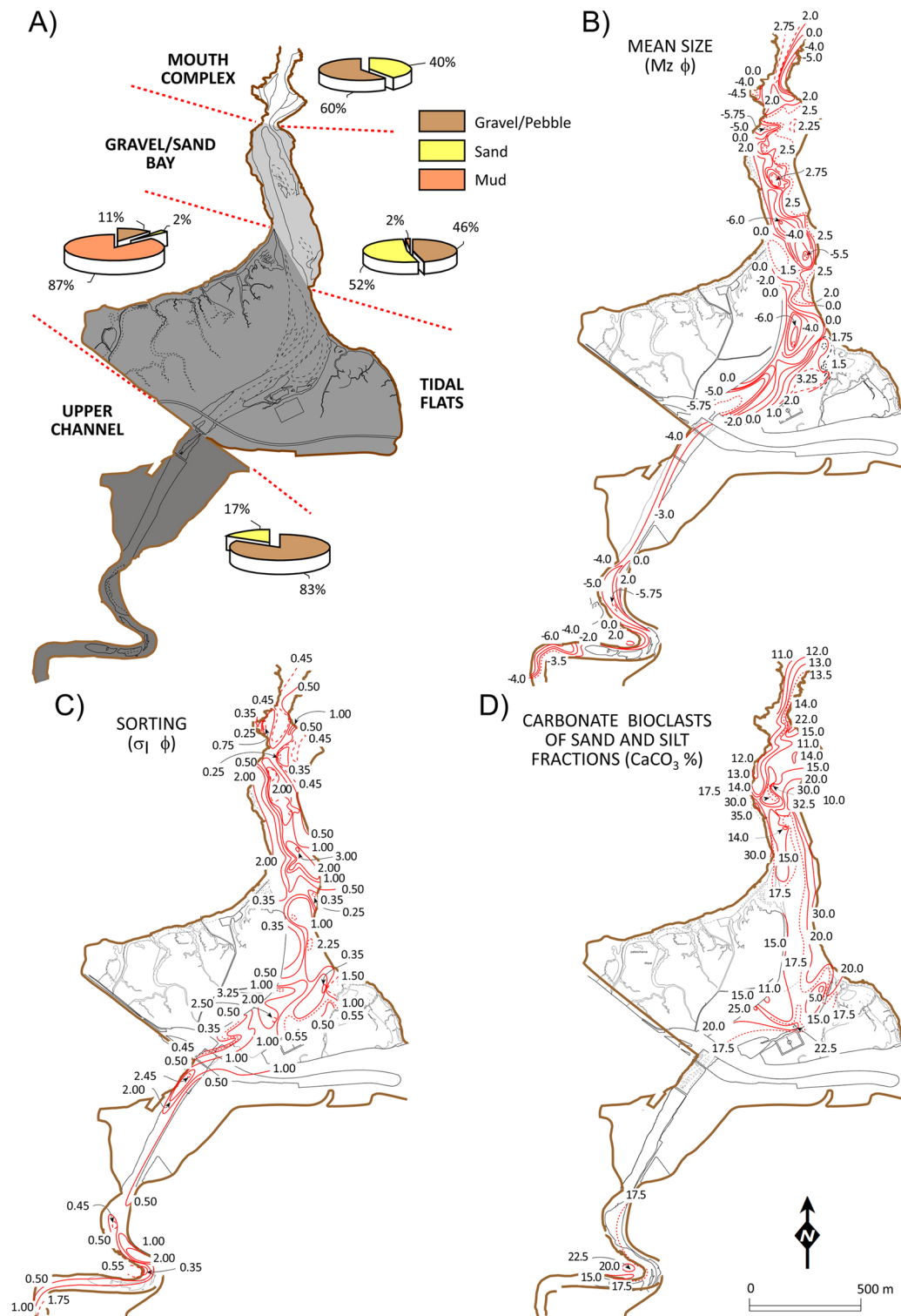
Fig. 5 A Surficial sedimentary fractions: gravel, sand and mud. **B** Main size trends (Mz) in phi units. **C** Sorting parameter trends (φ). (I) in phi units). **D** Biogenic carbonate trends (%)

The positive skewness of the sediment is remarkable (66%) indicating the unidirectional transport (channel) or sedimentation in a sheltered and low energy environment.

In the mouth complex, platykurtic to medium kurtosis are generalised, but in the bay the different morphosedimentary units are highly variable. The extreme high or

Table 3 Average values of the granulometric parameters, including the coarsest 1-percentile grain size, and the percentage of biogenic carbonates in sand and sand and gravel, characterising the morphosedimentary units in each estuarine zone (*n* = number of samples)

	Coarsest 1-percentile		Mean (Mz)		Sorting (σ_I)	Skewness (Sk_I)	Kurtosis (K_G)	Carbonates %	
	φ	mm	φ	mm	φ			only sands	sands and gravels
MOUTH COMPLEX									
Inlet-main channel (n=3)	0.87	0.55	1.60	0.33	0.48	0.05	0.72	—	11.66
Outer confining barrier (n=6)	-2.20	4.59	-0.18	1.13	0.51	-0.07	1.20	—	15.25
Inner confining barrier (n=4)	-6.83	113.77	-3.98	15.78	0.47	0.17	0.80	—	—
exposed gravel beach (n=4)	-0.25	1.19	1.94	0.26	0.92	-0.12	1.23	—	16.70
vegetated aeolian dune (n=1)	1.29	0.40	2.20	0.22	0.44	0.006	0.88	11.20	—
Western gravel embayed beach (n=4)	-5.41	42.52	-4.46	22.01	0.55	0.26	0.97	—	—
SAND AND GRAVEL BAY									
Main channel (n=2)	-6.07	67.18	-3.86	14.52	2.07	0.47	0.70	—	—
Longitudinal bars (n=13)	-5.22	37.27	-0.53	1.44	2.08	-0.05	0.93	—	17.87
Gravel and sand flat (n=15)	-1.79	2.46	2.54	0.17	1.39	-0.33	1.94	21.02	—
Sand tidal creek (n=2)	-4.21	18.51	2.46	0.18	2.09	-0.28	1.91	26.00	—
Mud tidal flats (n=3)	2.53	0.17	4.41	0.05	1.07	0.23	1.18	33.86	—
Northern estuarine gravel beach (n=2)	-0.07	1.05	2.24	0.21	0.47	-0.07	0.95	—	19.40
Southern estuarine gravel beaches									
northern estuarine beach (n=1)	-5.70	51.98	-5.27	38.59	0.23	0.08	2.05	—	—
southern estuarine beach (n=2)	-2.40	5.28	2.12	0.23	1.08	-0.27	1.79	—	20.90
Gravel lobe (n=2)	-5.45	43.71	-4.49	22.47	0.39	0.25	1.07	—	—
TIDAL FLATS									
Main channel (n=3)	-3.35	10.20	0.36	0.78	1.50	0.38	1.23	16.80	—
Point bar and longitudinal overlapped bars (n=11)	-3.98	15.78	-2.19	4.56	1.49	0.36	1.28	—	—
Northern longitudinal bar (n=3)	-6.23	75.06	-5.90	59.71	0.40	0.43	0.93	—	—
Southern longitudinal welded bars (n=2)	-6.16	71.51	-5.25	38.06	1.42	0.15	1.10	—	—
Western tidal flats (n=4)	1.23	0.43	4.17	0.06	2.41	0.01	1.31	16.86	—
Eastern tidal flats (n=3)	0.43	0.74	2.41	0.19	0.74	0.17	1.20	17.75	—
Tidal creek of Salcedo-Bustio port (n=2)	1.07	0.47	3.18	0.11	1.66	0.13	1.17	20.00	—
Eastern tidal creek (n=10)	0.83	0.56	2.32	0.20	1.48	0.43	1.35	—	—
UPPER CHANNEL									
Northern bars (n=2)	-6.02	64.89	-3.49	11.24	1.57	0.29	1.33	—	—
Eastern point bar (n=2)	-6.23	75.06	-3.86	14.52	1.42	0.34	1.14	—	—
Overflow sand sheet (n=1)	-0.33	1.26	2.10	1.26	0.54	0.20	1.02	22.50	—
Western overlapped bar (n=2)	-2.04	4.11	-0.13	4.11	1.26	0.21	0.87	—	18.00
Inner longitudinal bars (n=4)	-6.18	72.50	-2.34	5.06	2.78	0.70	1.04	—	—

low values of kurtosis imply that the sediment sorting was carried out elsewhere in a high-energy environment (Friedman 1962). Sediments that are finer in size and predominantly platykurtic in nature reflect the maturity of the sand, and the variation in sorting values is likely due to the continuous addition of finer or coarser materials in changing proportions. In practically all the tidal flats, leptokurtic values predominate, except in some longitudinal bars where the values are mesokurtic.

The scarce bioclastic sand content is attributed to a reworking of relict offshore sediments from the coastal submerged areas. In this case, the sandy submerged prism is reduced to a narrow valley fill at the mouth (Fig. 5D). Carbonates are more important in the bay, less so in the tidal flats, but they are represented in the upper channel despite the siliciclastic sand discharges of the Deva River. The outer estuarine area contains the minimum level of biogenic carbonates, probably due to the siliciclastic sand supply from the western coastal drift.

Mixing of fresh and saline waters

The mixing of waters was calculated from the river discharges (low and flood conditions) during a tidal cycle, and tidal prisms during spring and neap tides along the entire estuary (Fig. 2, Table 4). Previously, in situ investigations were carried out to determine the extent of the spring high tide and low river discharges in the inner estuary (Table 5; Fig. 6).

The data from the Deva River and its tributary, the Cares, was obtained from the *Comisaría de Aguas del Norte de España (Ministerio de Fomento)* dating back to 1940–1941, to calculate the fluvial runoff arriving at the upper tidal limit of the Tina Mayor estuary.

Table 4 Fresh water supplied by the Deva River and saline volumes (tidal prism), that are mixed in the estuary of Tina Mayor for different fluvial runoffs (flood and low flow) and spring and neap tides, as well as the average values

Fluvial discharges (m^3)			Water volume (m^3)
	River discharge in the mouth	Wettest year	1,498,890
		Driest year	553,780
		Average	1,032,490
Tide range (m^3)			Water volume (m^3)
Tidal prism		Spring tides	1,010,544
		Neap tides	270,840
		Average tides	593,628

Table 5 Variations of fluvial and tide volumes according to the flow ratio of Simmons (1955)

Q_F/QT	Maximum fluvial	Minimum fluvial	Average fluvial
Spring tides	1.53	0.58	1.05
Neap tides	4.13	1.56	2.83
Average tides	1.09	0.77	1.37

Data are from the Comisaría de Aguas del Norte de España (Ministerio de Fomento)

QF river discharge along a tidal cycle, QT tide prism

According to the stratification and characteristics of salinity distribution (Pritchard, 1956; Cameron and Pritchard 1963), the estuaries can be classified as salt wedge or strongly stratified, partially mixed and vertically homogeneous. The behaviour of the mixing of fresh and saline waters in this estuary is predominantly a salt wedge type, according to the results published by Simmons (1955) [QF/QT > 1.0 = mixing of salt wedge type, < 0.1 = vertically homogenous estuary and modifying the partially mixed type between < 1.0 and > 0.1]. During spring, average tides and minimum fluvial conditions, the estuarine reproduces a partially mixed type (Table 5). Nevertheless, in situ records of the salinity of the water column during a tidal cycle (Fig. 6) show that mixing waters are mainly vertically homogeneous. The saline content gradually varies from fresh water in the inner limit to saline water in the mouth along the flood tide. The mixing of water is more complex in the bay and between both inlets, developing salt-wedge structures, but not in all profiles nor at all tidal moments.

On the rising half tide, the distribution of water is mixed at the depth, simplifying an almost vertically homogeneous estuary, except in profile III (partially mixed). However, salinity at the mouth is high (> 25‰, profiles I and II) and from profile IV onwards, the influence of the fluvial flow becomes evident, with salinity dropping to below 5‰ (Fig. 6).

During high tides, the tidal flats and upper channel areas are dominated by salt wedge conditions and continental water in the inner estuary (from profile V onwards, Fig. 6). The outer belt shows a saline vertical record in the western margin (seawater) and a salt wedge type on the central and eastern sides due to the extrusion of mixed waters. The bay and the mouth complex are better represented by a vertically homogenous saline structure.

When tide falls, almost all the mixing waters take on a vertical structure, more saline on the western side of the mouth complex and slightly fresher on the same bank on the inner estuary.

The surficial salinity distributions provide insight into the flood and ebb tendencies during each tidal cycle (Fig. 7). The geometry of the curves is a clear sign of the water movements. The convexity of isohalines upstream indicates that the saline waters are coming to the inner estuary and that fresh and mixed waters are extruding to the mouth. As can be deduced from Fig. 7A (half rising tide), the fresh water types meet between the isohalines of 10.0‰ and 25.0‰, and saltier waters are coming up on the western side, while fresher waters are situated on the eastern side. The marine waters are mostly located in the estuarine mouth, but mixed waters (25.0‰) are moving downstream on the eastern side. During high tide, saline water is intruding mainly from the western side increasingly slower until the levelling-off or equilibrium tidal phase (Fig. 7B). In the bay, there is a slight tendency of a flow on the eastern side, marked by the isohaline 33.75‰, and some mixed waters draining the southeastern active marshes of the tidal flats, join the main saline waters occupying the main channel. Finally, the falling tide is characterised by the extruding mixed waters mainly moving along the entire eastern side of the estuary, but other residual ones dilute in the bay with probably weak flow and ebb currents (Fig. 7C: 15.0‰ and 10.0‰ isohalines).

Circulation dynamics

The Tina Mayor estuary is characterised by large fluvial discharges due to the fact the Deva River is one of the mightiest on the Cantabrian Range. However, this degree of fluvial
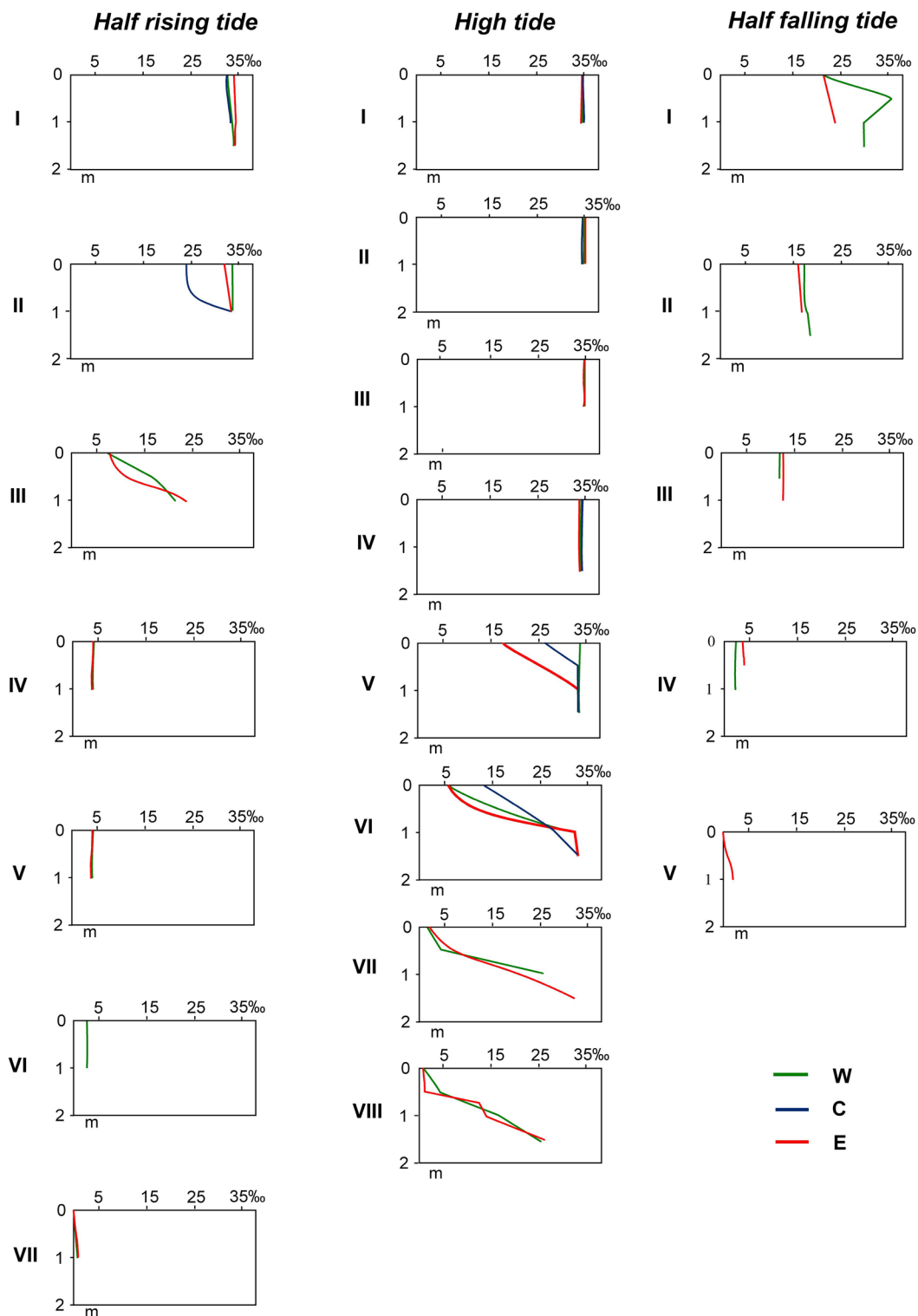
Fig. 6 Vertical salinity records from the surface to the bed at three tide phases: half rising tide, high tide and half falling tide

influence also depends on the tidal momentum over a period of twelve hours, which is why a comprehensive record was made, proposing eight profiles during a complete tidal cycle from the mouth of the inner estuary (Fig. 2).

The dynamics at the mouth are characterised by the action of waves coming with a more pronounced component from the NW, refracting and penetrating according to a NE–SW trend in both barriers and promoting an upcurrent drift along
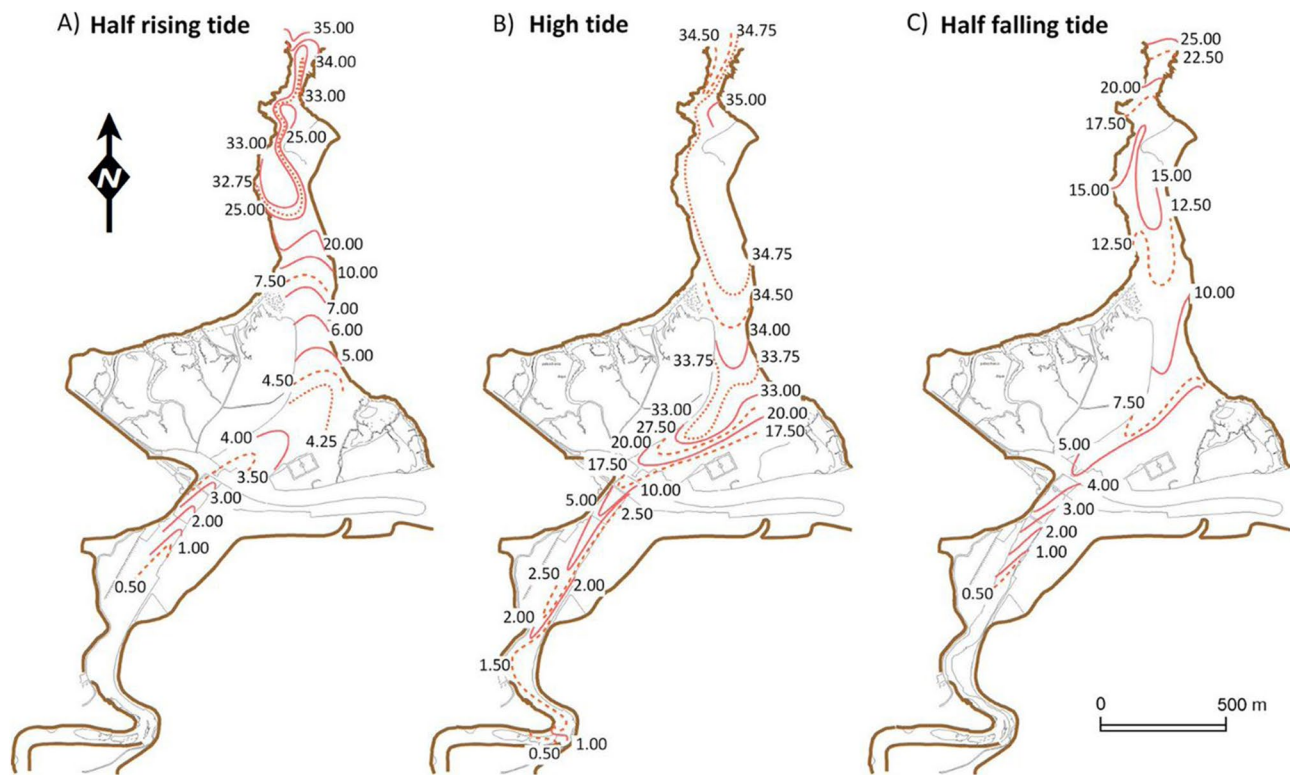
Fig. 7 Surficial salinities simplified in the three most important intervals of a tidal cycle. Distribution during low tides are not significant as mixed waters are extruded through the channels

the eastern margin. This causes the main channel to be permanently located in the western area.

Figure 8 shows the model of circulation obtained by the direction and sense of currents when they are recorded simultaneously with the salinity in the water column during the tidal cycle. The flow velocities are grouped in the three most representative categories, intensive (≥ 1.0 m/s), moderate (0.5–1.0 m/s), and weak currents (≤ 0.5 m/s). Furthermore, bottom currents have been included, taking into account the same categories. Some records exceed speeds of 1.50 m/s, especially in the inner inlet during half rising tide and relatively long intervals of time during ebb tide, as well as in the proximity of fluvial influence.

During low tides in this shallow and narrow estuary, the morphosedimentary units emerge, except in the channels. Due to the tidal cycle, the salinity and currents constantly change more sharply than those filled with sediment. The saltwater inflows at the bottom of the water column, while the river freshwater outflows near the surface, travelling above the saltwater layer. If there is a subhorizontal interphase of salt or fresh water, the low mixing of waters determines a salt-wedge or highly stratified estuary. The simplified circulation patterns were determined according to four extreme and representative tidal phases, low tide, half

rising tide, high tide and half falling tide, each one covering an interval of at least an hour and a half.

The resulting measure velocities of the water currents vary from strong to moderate in intensity, with a control of the seasonal fluvial runoff being more important in the main channel, where bathymetries are deep, and the water can concentrate. This is particularly important during low tides, due to all waters being extruded (Fig. 8A) when the flow of mixed waters (mainly fresh waters) is led through the main channel and tidal creeks, largely following a unidirectional river model. In the inner estuary, where fluvial influence is strong, point and longitudinal bars are activated and erosive banks can be produced, especially during floods. More intensive currents are generally detected in the main channel and where the tributaries meet the main channel. Also, they are important in the inner inlet and in a sector situated on the southern side of the tidal flats (tidal creeks).

During half rising tide, there is a trend where the saline water penetrates the western margin and the mixed and fresh waters outflow along the opposite side (Figs. 7A, 8B), which continues during high tide (Figs. 7B, 8C). This is a consequence of the Coriolis effect. This lateral segregation is well defined along the inner estuary in all tidal cycles (Fig. 8). However, the confining areas can modify the inflows and
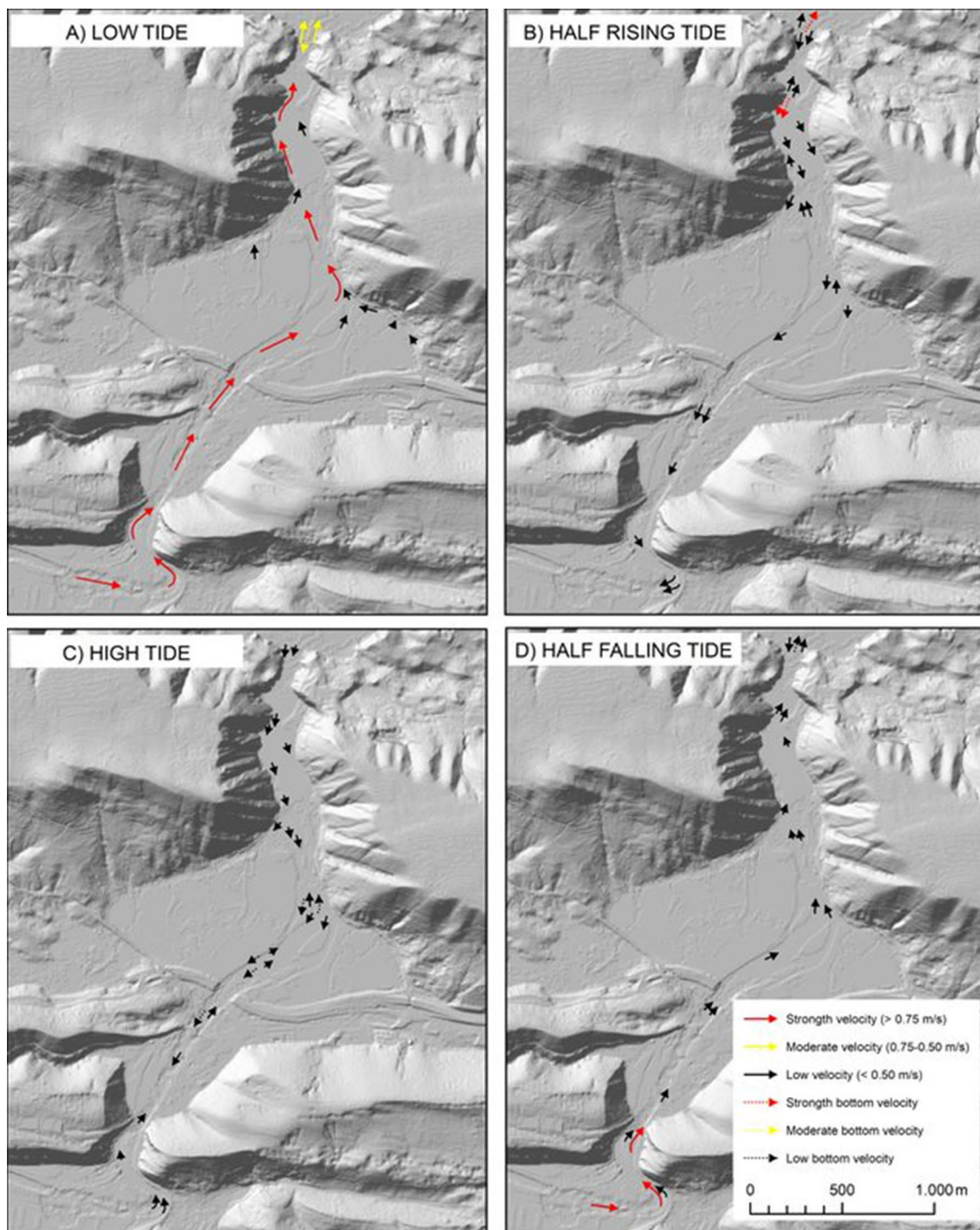
Fig. 8 Simplified scheme of surficial and bottom currents in a tide cycle

outflows according to this trend as they do in the bay, where strong flows during half rising tides are deviated to the south-eastern side (Figs. 7A, 8B). The levorotatory gyre is again reproduced in the channel in the tidal flats sector (Fig. 8B). In the rest of the estuary, the currents are inflowing with velocities not exceeding 0.5 m/s.

The dynamic behaviour of the estuary is different during high tide (Fig. 8C), as the rocky confinement concentrates the flow currents along the mouth and the bay and there are only ebb-tidal currents along the eastern margin in the main channel that runs through the tidal flats. Therefore, in this area, the Coriolis effect occurs with low to moderate currents.

However, during the half falling tide (Fig. 8D), all outflows are both on the surface and deep, being much stronger in the upper channel. Only at the mouth does the Coriolis effect occur again, with seawater entering from the western side and ebb currents from the opposite side.

Discussion

Morphology, sedimentation and dynamics

Estuaries are generally considered to be sediment traps, filled with riverine, offshore or coastal sources (Biggs and Howell 1984). Furthermore, empirical studies have documented some of the predominant controls in the influx rates of these, including sea-level rise, climate, and estuarine dynamics on estuarine infilling (Schubel 1984).

From a morphological point of view (Fairbridge 1980), most Cantabrian estuaries are characterised by a single mouth spit and, in the case of Tina Mayor, by two, the inner and the outer, both of which consist mainly of gravel and pebbles. However, peninsular estuaries can be divided into four sectors (Flor 1995), the mouth complex, bay, tidal flats, and the upper channel. The corresponding morphosedimentary and dynamic units (sedimentary facies), have greater variability from one estuary to another, but the main channel, tidal creeks, confining barrier, including a vegetated dune, tidal flood delta, estuarine beaches, and many bedforms and bioturbation structures are well represented in Tina Mayor. Moreover, in this gravelly estuary, the spill-over lobes (Figs. 3, 4B), confining barrier (Fig. 4C), large gravel bars (Fig. 4D, E, F) bedforms (Fig. 4G, H, J, K, L), and scours (Fig. 4I) are developed, decreasing the bioturbation structures with respect to sandier estuaries.

Following the criteria set forth by Dalrymple et al. (1992), these kinds of estuaries are classified as wave dominated. Nevertheless, in Tina Mayor the waves are only significant at the mouth and in the outermost part of the bay. In this case, King (1980) and Allen's (1993) classification as a rock-bounded estuary would best fit with its morphology and with similar characteristics as the neighbouring estuary of Tina Menor (Flor-Blanco et al. 2015a).

This estuary, drained by the Deva River, as well as the neighbouring Tina Menor (Nansa River), are the main contributors of sediment to the east, thanks to the littoral drift (Flor-Blanco et al. 2015a), and despite a theoretical tendency to fill. The wide hydrographic basins of these rivers (Fig. 1) and the notable supply of sediments during the floods, mainly siliciclastic, have allowed a part of the contributions that configure the neighbouring estuary of San Vicente de la Barquera (Flor-Blanco et al. 2015b), as well as the development of wide beaches and dune fields to the east.

There are three sedimentary environments identified in Tina Mayor:

1. River gravels and sands that derive from the hydrographic basin.
2. Marine sands that come from beaches and the adjacent shore environment.
3. Silts and clays.

The latter are deposited in the sheltered central basin (Carvalho and Woodroffe 2020), mainly as a suspended load discharged during river floods to which the organic matter and biota must be added, both brought by river discharges (plant remains) and the estuarine infauna developed in situ due to shell organisms and worms.

A very few estuaries transport gravel and larger size sediment and the sand is typically composed of quartz. In this estuary, the most important fluvial sediments are represented by quartzitic gravels and siliciclastic sands deposited by high discharges, as well as muds and organic matter that are fixed as marshes, but mostly reclaimed. The sands are recycled fractions from previous coastal sediments as evidenced by the fact that they contain biogenic carbonates. However, in proportions lower than 35%, these are more important in the outer belt of the mouth complex linked to the inner continental shelf. These sands have penetrated the inner estuarine areas and gravel fluvial discharges have been occurring in the last few decades.

The Tina Mayor estuary is an excellent example of sedimentation dominated by coarse fractions (Table 3). On the other hand, it is assumed with most estuaries that the landward zone (upper channel) is dominated by riverine sedimentation constituted by gravel, gravelly sand and sandy gravel (Fenster and FitzGerald 1996). In estuaries in other latitudes, such as glacial types, sediments are coarse (gravel and cobbles) and reworked by wave action (Cooper 2004). Moreover, most studied gravel barriers in glaciated coasts with heterogeneous sediments were actively sorted by waves (Orford et al. 1996). Other estuaries, such as in northern New England, export coarse-grained sediments to the nearshore (FitzGerald et al. 2005). However, the river-dominated estuary is discussed by Cooper (1993) in South Africa in a subtropical climate as the result of the impact of periodic floods (Mgeni River estuary), being filled by coarse fractions of fluvial supply. Some of these sedimentary similarities can be applied to our case study, except that a coastal sandy prism is not built, and the sand infill of the paleo-valley continues to an approximate depth of 30 m.

Grain size parameters will reflect the spatial and temporal variations in the transport mechanism and flow direction (Anthony and Héquette 2007), because estuaries are in a constant state of change and grain size parameters are employed to interpret sediment motion. In the spatial distribution of
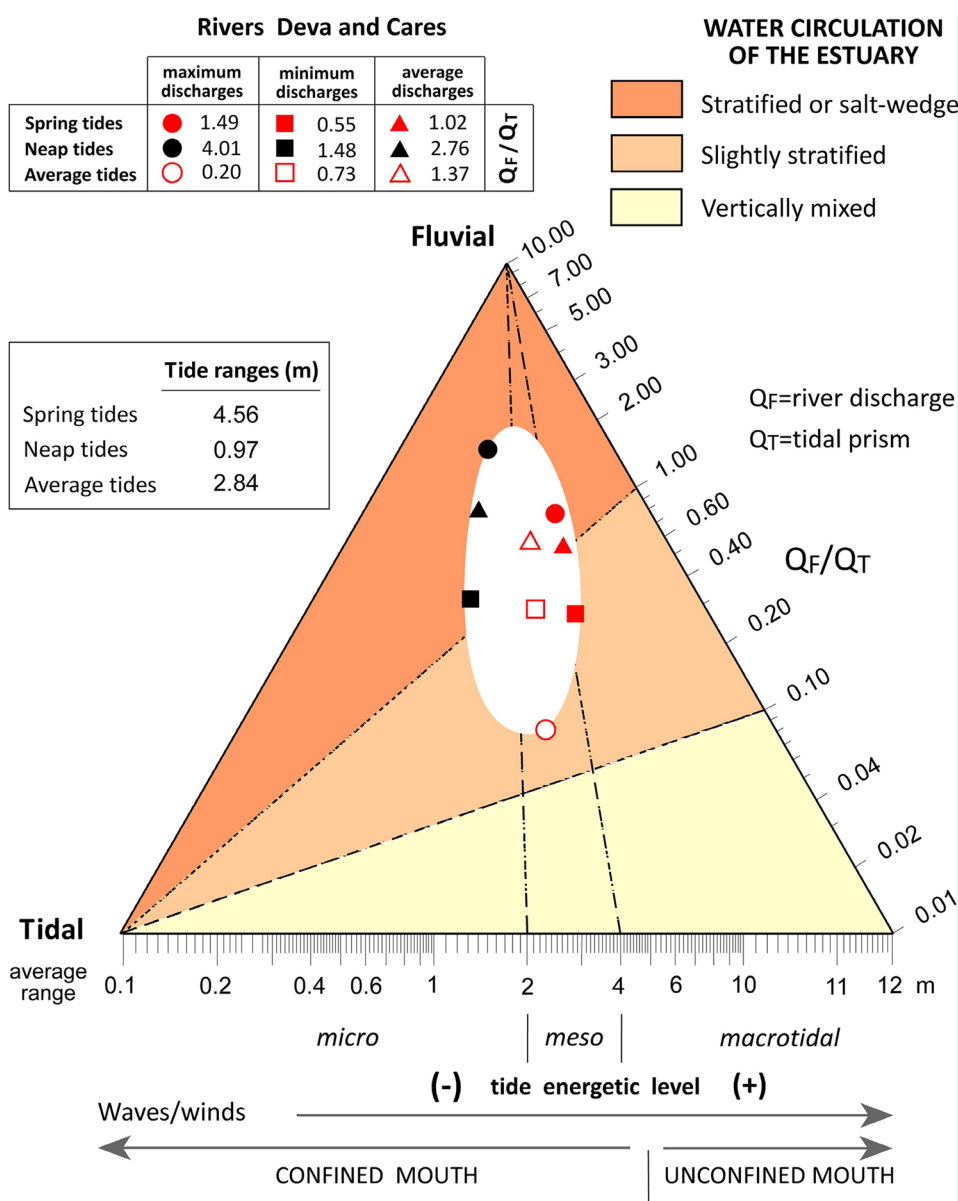
sediments in estuaries, it is customary to know the relationship between the statistical parameters and patterns of transport (Zhang et al. 2013). For instance, in Tina Mayor, fluvial bars and beaches of the confining barrier contain larger sizes, corroborated by the centile, mainly in the upper channel. The sediments deposited in the mouth complex are well sorted, deteriorating upstream in most of the facies represented, and are better on some sandy facies, on the aeolian dune, gravel lobe and estuarine beaches (bay), and the sand overflow sheet (up channel). The skewness parameters are almost positive in the mouth complex, predominantly negative in the bay and very positive upstream. Curves are flatter at the mouth and sharper in the rest of the estuary.

The relationship between grain size trends and sediment transport can infer their patterns. It is generally agreed that the faster the current, the greater the sediment size that a stream can move, and the mean grain size decreases (Self 1977) or increases in the direction of the transport (Nordstrom 1989). The models of one- (McLaren and Bowles 1985) and two-dimensional approaches (Gao and Collins 1992; Le Roux and Rojas 2007; Yamashita et al. 2018), use parameters of mean, standard deviation, skewness and kurtosis to deduce the main transport, as has been done for Tina Mayor. Decreasing in grain size, better in sand-size sediments, it is progressive sorting during transport (Bartholomä and Flemming 2007).

Regarding the physico-chemical properties of the water within the estuary, the processes of mixing fresh and saline waters have been used as a first approach to document estuarine circulation (MacCready and Geyer 2010). Consequently,

Fig. 9 Global rates between river and tide volumes based on data obtained from the Comisaría de Aguas del Norte de España and the Servicio de Puertos del Estado (Ministerio de Transportes, movilidad y agenda urbana) in the estuary of Tina Mayor. Tide ranges are considered to be quantitative values from spring to neap tides

Rivers Deva and Cares						
	maximum discharges		minimum discharges		average discharges	
Spring tides	●	1.49	■	0.55	▲	1.02
Neap tides	●	4.01	■	1.48	▲	2.76
Average tides	○	0.20	□	0.73	△	1.37

Tide ranges (m)	
Spring tides	4.56
Neap tides	0.97
Average tides	2.84

WATER CIRCULATION OF THE ESTUARY
- Stratified or salt-wedge
- Slightly stratified
- Vertically mixed

Q_F = river discharge
Q_T = tidal prism

Q_F/Q_T

Fluvial
Tidal
Waves/winds
(−) tide energetic level (+)
micro | meso | macrotidal
CONFINED MOUTH | UNCONFINED MOUTH

different mixing guidelines have been proposed to classify estuaries (Pritchard 1967). Taking into account the average numerical values (flow ratio) put forward by Simmons (1955) regarding the mixed saline and fresh waters, this study proposes a triangular classification diagram where these variables are collected (Fig. 9), previously validated in other studies (Flor-Blanco and Flor 2019). This triangular diagram shows that the behaviour of the mixture of waters (QF/QT) in the Tina Mayor estuary is mainly highly stratified or a wedge type except at average tides for maximum and minimum discharges and spring tides and minimum discharges, in which cases they fall into the category of slightly stratified (Fig. 9). However, in salinity measurements during a complete tidal cycle (spring tide and mean river discharge) the estuary behaves in a vertically homogeneous manner in

the outer and inner part of the estuary. Only during high tide, does it stratify towards the inner half (Fig. 6).

In an estuarine fill, the main factors are: (1) the amplitude and rate of sea-level change (rise), (2) the inherited morphology of the substrate, and (3) the establishment of coastal hydrodynamics such as tides, river and waves (Gregoire et al. 2017). A proposal of the interaction between the morphosedimentary and dynamic trends can be done in the estuary of Tina Mayor, including the hydrodynamic factors such as waves in the outer estuary and those generated by winds during high tides, tidal currents, and river discharges. A hypothetical model has been developed for the long term (Fig. 10).

Datasets were analysed, including river discharges, tidal currents, mixed waters, winds and wave activities, to combine with sedimentary surveys, cartographic mapping of the more important morphosedimentary units, granulometric

Fig. 10 Conceptual model of the estuary of Tina Mayor taking into account the major dynamic influences longitudinally through the four defined zones
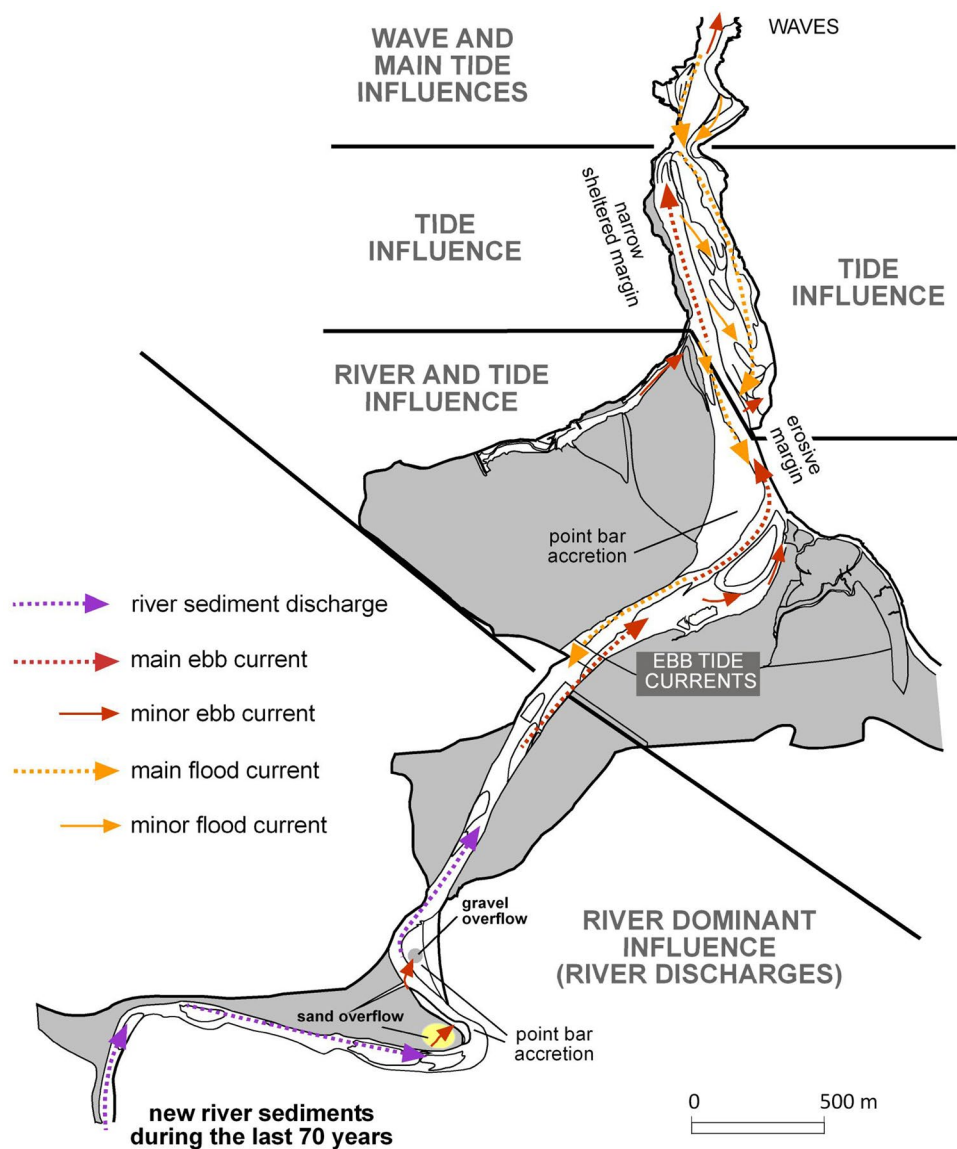
parameters, the sand carbonate content, and large bedforms. In Tina Mayor, as in other estuaries, circulation dynamics play a critical role in its physical, sedimentary and transport processes. Salinity distribution can strongly influence residual water motion and subsequently affect tidal transport of sediment, pollutants and other waterborne materials (Wei et al. 2014; García-Ordiales et al. 2018, 2020b; Guevara et al. 2021), and which can be extruded out of the estuary, as has been demonstrated in Asturias (Sanz-Prada et al. 2020).

The most important dynamics and sedimentation are restricted primarily to the main channel and marginal bars, with a decisive river influence containing high proportions of gravel, as has also been established in the estuary of Ribadesella (Asturias), studied by Flor and Camblor (1989). This type of estuary is not common in the Iberian Peninsula, with only a few examples in other parts of the world such as the Rio Grandes estuary in Tierra del Fuego in Argentina (Isla and Bujalesky 2004). Although the wave is the predominant factor in low energy beaches (Jackson et al. 2002), it can also be deduced that on the beaches of the southern end of the bay of Tina Mayor, an intervention of strong flood-tidal currents erodes the top of the gravel beaches, including a fetch of 750 m by winds from the NW during high spring tides.

Evolutionary patterns: morphodynamic and sedimentary model

The interpretation of this conceptual model is dependent on the fact that during low tides, the water flows through the main channel and some tidal channels at low flows with a sedimentary transport seaward. The outer barrier further narrows the mouth and the incident wave is refracted, generating a drift current along the large gravel spit (inner confining barrier), this sector being the most influenced by waves and tides (Fig. 10). During rising tide, the intrusion of saltwater develops strong flood currents, generating a wide elongated spill-over lobe where several discontinuous bars are generated just east of the main channel. The entire dynamics of the bay are mainly influenced by the tides, except during the ebb tide, when the river is particularly strong (Fig. 10).

The Coriolis effect is restricted only to the mouth and the beginning of the fluvial influence, once the rocky narrowing is over (Fig. 10), as in the bay the structural control deflects the flow currents towards the SE. This same behaviour has been reported in the neighbouring estuary of Tina Menor, located 4.0 km eastward (Flor-Blanco et al. 2015a), and is also a confined, rocky estuary characterised by sand. However, in other sand broad bays the saltier waters and inward currents run through the west side from low to high tide, as in the estuary of San Vicente de la Barquera, located 10 km to the east (Flor-Blanco et al. 2015b). Similarly, this nearby estuary develops a flood-tidal delta, generating a counterclockwise surficial current from the half rising tide to high tide as a result of the Coriolis effect. This is impossible to develop in Tina Mayor due to the narrow and detailed morpho-structural control.

The marshes, which have largely been anthropised, restrict their dynamics to some tidal channels, such as that where the port of Bustio is located, but mainly in the main channel, this port being classified as a coastal tide gate (CT) according to Finkl (1998).

On the other hand, the inner estuary is historically dynamic (influenced by the river), manifested by the appearance of new fluvio-tidal bars and the increase and stabilisation of numerous bars, many of them moving downstream into the middle estuary (Fig. 10).

Meteorology is a major influence throughout the river basin, and for this reason, changes in precipitation could affect soil erosion, and might also be a considerable factor in modifying fluvial regimes (De Luis et al. 2010). When precipitation increases, run-off changes (Roper et al. 2011), and it is produced in a greater volume of clast supply from rivers to estuaries. From 1985 until 1993, rainfall increased substantially (Domínguez-Cuesta et al. 1999), exceeding 2000 mm/year in the head of the Deva and Cares Rivers in Picos de Europa, with a pluviometric increase in autumn and the spatial extension of the autumn maximum. This may be the cause of a greater input of gravel in the estuary from the Deva River, especially considering the usual time lag between the processes triggered in the basin and the sediment input. However, in the period from to 1951 to 1980, the annual rainfall of Cantabria as a whole was 1,333 mm/year, while from 1981 to 2000, the average was 1209 mm/year, 10% lower (Ancell Trueba and Celis Díaz 2014).

From the evolutionary point of view, this estuary is largely silted up. Based on data from the Santander tide gauge, the trend of an increase in mean sea level over a period of 67 years (1943–2010) is 2.38 mm/year (García et al. 2012), although no significant variations could be detected in the mouth and bay of the estuary, except for the reduction of the tabular dune surface in the inner mouth spit, mainly due to the recurrence of strong storms on the Cantabrian coast since 2006 (Flor-Blanco et al. 2021). This dune erosion pattern has been very common throughout the Atlantic and Cantabrian Sea (Bay of Biscay) (Pye and Blott 2008; Masselink et al. 2016; de San José et al. 2018; Flor et al. 2019).

It is widely accepted that a human-driven, global geomorphic change is taking place, and has particularly intensified since the mid-twentieth century, coinciding with a period of intense change known as the Great Acceleration, although the main driving agent is less clear (Cendrero et al. 2020). Other studies in the Basque Country have analysed extraordinary episodes of rainfall, with quantity and intensity driving multiple landslides (Rivas et al. 2020). These sediment inputs from watersheds or the effect of strong storms, accelerate estuarine

infilling and these patterns have increased since the beginning of the previous century and have already been calculated in several Cantabrian and Atlantic estuaries in relation to natural factors (rainfall) and human activity (Bruschi et al. 2013). The monitoring has also detected the morphological and sedimentary changes in the interior of many of the Cantabrian estuarine systems (Flor-Blanco and Flor 2019), which, in contrast, are directly related to the impact of climate change in terms of sea-level rise and, above all, to the recurrence of extreme storm wave events (Guisado Pintado and Jackson 2019; Castelle and Harley 2020a, b; Flor-Blanco et al. 2021) that favour massive sediment intrusion into estuaries. A clear example has been seen in San Vicente de la Barquera with significant loss of saltmarsh vegetation due to sediment intrusion (Aranda et al. 2020a), but also other types of ecological changes in estuaries and deltas (Aranda et al. 2020b). While in other parts of the world, climate change is linked to human influence (Chen et al. 2019). This trend has been studied for estuaries in the UK, where the sea-level rise will cause some marine habitats to expand and others to change by surface, while increased temperatures, salinity and changes in precipitation patterns can be extrapolated to shifts in biota, eutrophication and even increased pollution (Robins et al. 2016).

The forecast for the future is that the rate of estuarine infilling and the migration of morphosedimentary units inland will increase, completely changing the present configuration. In several Cantabrian estuarine systems, climatic variations during the Holocene have been reflected in sediments, as in the case of Gijón (Flor and Lharti 2008), San Sebastián (Edeso-Fito et al. 2017) and Pasaia (Irabien et al. 2020), and others completely filled, such as Guadamía, Poo and Purón in the northeast of Asturias and a few tens of kilometers from the study area (Flor-Blanco et al. 2022).

Conclusions

The estuary of Tina Mayor is an excellent example of a gravel mesotidal estuary that is filled through a narrow, long, and carved fluvial valley with two confining barriers along the rocky narrowing of the mouth. This is the most complete study carried out in this type of estuary in the whole of the Iberian Peninsula, as it is approached from a sedimentary, physical–chemical, dynamic and morphological point of view.

It can be classified mainly as a highly stratified or wedge type, and during low river flows and spring and average tides, it is a partially mixed estuary.

Four geomorphological zones can be differentiated from the mouth to the inner estuary, each dominated by some sedimentary fraction, namely mouth complex (gravel and sand),

bay (gravel), highly reclaimed tidal flats (gravel and muds) and upper channel (gravel and sand).

It should be noted that one of its peculiarities with respect to other estuaries is the presence of two confining barriers at the mouth, where the outer incipient barrier is mixed (gravel and sand), and the inner is constituted by a gravel emerged spit, both anchored on the eastern side. This part is controlled by waves refracting NE–SW and tide flood currents are considerable in the western side as the tide rises.

On the other hand, contrary to the normal Coriolis effect (levorotatory), the morphosedimentary distribution in the bay depends on the rocky narrowing of the mouth that diverts flood currents and sediments to the eastern margin during half rising tide. The morphological development of the bay is entirely conditioned by this rocky confinement, so a wide elongated bar is formed, being assimilable to a spill-over lobe. In this bay area, the geometry of gravel bars, spill-over lobes and simple lobes, as well as other minor bedforms, mainly gravel, allows one to deduce local and residual currents to understand the entire sediment dynamics during the half rising tide and during a period before low tide. This gyre mainly develops at the mouth and in the main channel of the tidal flats during high tide and half falling tide.

Coarse fractions represented by gravels are distributed in the upper channel zone and bimodal (gravel and mud flats) in the tidal flats. Gravels and minor sands with a relatively high carbonate percentage are found in the bay, correlating with stronger energy during half rising tides, and mainly sands are located in the mouth complex. The best sorted sediments are in the mouth and these gradually worsen towards the inner estuarine limit.

In recent decades, river gravel supplies have continued to fill the upper channel estuarine zone and migrated to the central estuary, generating new lateral bars, growing other existing bars and fixing old ones with vegetation and it would seem that there is no significant sedimentary intrusion from the outside. However, due to the rise in sea level, the future trend of all Cantabrian estuaries is the gradual migration of the system towards its internal sector.

Based on the work of other authors, a triangular classification is presented, using the calculation of river and tidal flows, in relation to the type of mixing that occurs in the estuary for different tidal moments and river discharges. For this case, it would be an estuary that ranges between stratified or salt wedge and slightly stratified. Moreover, a conceptual model of currents, sedimentation and marine or fluvial influences has also been obtained for such a complex estuary.

Declarations

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