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The impact of man on the morphodynamics of the Huelva coast (SW Spain)

Efectos antrópicos en la morfodinámica de la costa de Huelva (SO España)

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Abstract

The Huelva coast is composed by large sandy beaches and spits, only interrupted by the presence of the estuarine mouths of the Guadiana, Piedras, Tinto-Odiel and Guadalquivir which are in an advanced state of sediment infilling. The morphology and processes of the Huelva coast are mainly linked to tidal regime, wave action, coastal-drift currents, fluvial dynamics, climatic change and anthropogenic activity. In the last five decades anthropogenic activity has modified the natural dynamics by the construction of jetties, docks, harbour and coastal developments. The main consequences have been the interruption of the sedimentary bypassing caused by an active west-to-east littoral drift, the modification of the tidal regime, the wave refraction-diffraction scheme and the intensification of the littoral erosive processes. All these effects will increase with the slow sea-level rise, close to 0.6 cm per year, which will induce a higher efficacy of the erosional events. A future retreat of about 10-15 m of the coastline is estimated.

Keywords: Morphodynamics, anthropogenic influence, coast, Huelva, SW Spain

Resumen

La costa de Huelva esta constituida por extensas playas y flechas litorales, interrumpidas por la presencia de grandes estuarios (Guadiana, Piedras, Tinto-Odiel y Guadalquivir) en un estado avanzado de colmatación. La morfología y los procesos de la costa se deben principalmente a una serie de factores: régimen mareal, olas, corrientes de deriva, dinámica fluvial, cambio climático y la actividad antrópica. En las últimas cinco décadas la actividad antrópica ha modificado la dinámica natural debido a la construcción de espigones, escolleras, puertos y urbanizaciones. Las principales consecuencias de esta actividad han sido la interrupción del trasvase de sedimentos del Este hacia el Oeste por la corriente de deriva litoral, la alteración del régimen mareal, la modificación de los procesos de refracción-difracción de olas y la intensificación de los procesos erosivos. Todos estos efectos se verán incrementados con el paulatino ascenso del nivel del mar en el Golfo de Cádiz, del orden de 0,6 cm anuales, repercutiendo en una mayor eficacia de los eventos erosivos. Se estima una pérdida del orden de 10-15 m en el perfil de las playas.

Palabras clave: Morfodinámica, influencia antrópica, costa, Huelva, SO España

1. Introduction

Coastal sedimentary environments are natural systems functioning under intense dynamic controls that induce continuous morphological changes, creating a situation of unstable balance. The geomorphology and stratigraphy of these environments are controlled by three main factors: relative sea-level changes, sediment supply, and coastal hydrodynamic processes (Davis *et al.*, 1987; Cowell and Thom, 1994). The possible combinations of these three factors generate different coastal morphostratigraphic models. Human activity on coasts can directly modify two of the three factors: sedimentary supply and coastal processes. These modifications generate important sedimentary disorders reflected in critical changes in the physiography and evolution of coastal environments (Morales *et al.*, 2004). The detailed study of the characteristics of human modifications on coastal systems and their response allows the creation of predictive models that can help to minimize the consequence of future construction on the coast. The objective of this work is to determine the changes and alterations of the coastal environment produced by man on the Huelva coast in the last decades.

2. Study area

The Huelva coast is located in the north sector of the Gulf of Cadiz, in the south-western portion of the Spanish coast and it is one of the most populated regions of Spain (Fig. 1). It is also an important touristic area, being visited by more than one million people between May and September. Human activity on the coast has become very intense since the second half of the 20th century. This activity has been mainly due to the construction of jetties, docks, harbours and coastal resorts.

2.1.Physiography and hydrodynamic features

The Huelva coast is composed of large sandy beaches (145 km long), interrupted only by the presence of estuarine mouths of the Guadiana, Piedras, Tinto-Odiel and Guadalquivir rivers. All of these are in an advanced state of sediment infilling (Fig. 1). The origin of these estuaries is the result of the gradual rise of the sea level during the present interglacial period (the Flandrian transgression). The rapid sea-level rise following the final phase of the Last Glacial Maximum caused a rapid and marked coastal retreat along the whole South-Atlantic Iberian coast. The lower river valleys were transformed into wide rias which developed estuarine circulations, and the coastal promontories and flanking headlands were eroded into cliffs. Coastline retreat was helped by gentle topographical slopes and a unvegetated shores formed basically of weakly-cemented Neogene and Quaternary sands. Large quantities of sediment were available, and this was transported along the whole coast and deposited mainly in estuaries, dunes and submerged parts of the continental platform. The high rates of coastal erosion and the intense supply of fluvial detrital sediments helped to infill the rias.

Once the transgressive maximum was reached (6500 years BP according to Zazo *et al.*, 1994), the dynamics generated favoured the regulation of the coastal profile. The filling of the estuaries and the development of estuarine sedimentation were favoured by the formation of barrier islands, spits bars and marshes.

The Guadiana, Piedras, Tinto-Odiel and Guadalquivir estuaries are partially closed by the large spits of Monte Gordo, El Rompido, Punta Umbria, Punta Arenilla and Doñana, respectively (Fig. 1). The morphology of spits comprises a strand plain of beach ridge and swales and successive trains of dunes.

The littoral physiography of this area is mainly linked to five morphodynamic factors: tidal regime, wave action, coastal drift currents, fluvial dynamics and artificial jetties. The tidal regime is mesotidal (Davies, 1964) or high mesotidal (Hayes, 1979), with a mean range of approximately 2 m (Borrego and Pendón, 1989). Wave energy is medium (75 % of the wave heights do not exceed 0.5 m (CEDEX, 1991)) and has an important seasonal variability and is higher during the winter storms (December-January).

The alongshore currents have the greatest effects on the sediment redistribution of this littoral. The net sediments flow is eastwards, with a high annual sediment transport of 180,000 to 300,000 m^3 in this direction (CEEPYC, 1979; Cuena, 1991). This transport is particularly important in the morphological variations of the shoreline owing to the orientation of this coastal sector, which open to the southwest waves. These conditions favour the development of broad littoral lowlands, usually sheltered by spits (El Rompido, Punta Umbria, Doñana), where intertidal-flats, salt and fresh-water marshes extend several kilometres inland.

Two rivers (Guadiana and Guadalquivir) are the main sediment source of the Huelva littoral, with a mean discharge of 144 m^3s^{-1} and 185 m^3s^{-1}, respectively (Vanney, 1970). The other rivers (Piedras, Tinto and Odiel) have very limited flows, and have little importance in the sedimentary dynamics of the southwestern Spanish coast. In addition, the sediment transport capacity of these five riv-

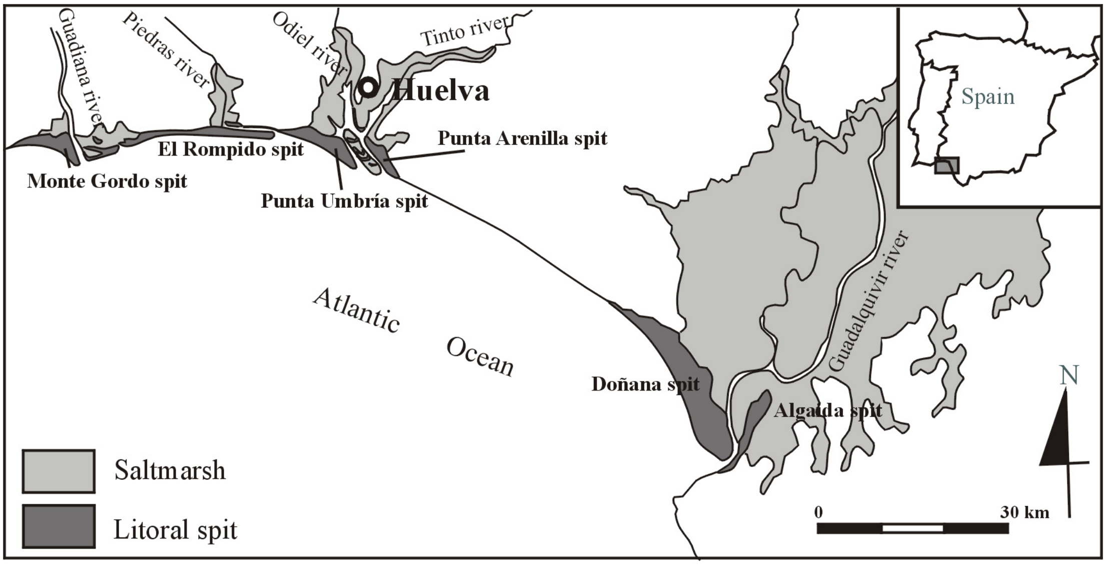

Fig. 1.- Location map of the Huelva coast.
Fig. 1.- Mapa de localización de la costa de Huelva

ers has decreased since 1960, with the construction of 65 dams regulating over 75 % of the flow (Ojeda, 1988).

This coast is heavily defended with modern protective jetties, causing either total (Vila Real do Santo António, Huelva) or partial (Isla Cristina, Punta Umbria) obstacles to the alongshore sedimentary transport. Consequently, two sedimentary units (Ayamonte-Punta Umbría and Mazagón-Doñana) may be delimited in this anthropogenically-altered area, directly related with the effects of the main jetties (Ojeda, 1988). Each unit includes two different zones: a) affected by erosive processes (Ayamonte, Isla Cristina, La Antilla, Punta Umbría, Mazagón, Matalascañas); and b) affected by progradational processes (El Rompido and Doñana spits), both spits are the least-altered, prograding areas of this littoral. Their geomorphologic characteristics include well-developed beach-ridges and swales.

3. Methodology

Diverse detailed cartography of the Huelva coast has been made using historical charts, and aerial photographs to provide data about coastal evolution in the last decades, before (earlier than 1960) and after the main anthropogenic transformations (1960 to present) to determine the processes of erosion and sedimentation along the coast during both intervals. In order to quantify the rates and total amount of coastal retreat and progradation during the last decades, aerial photo-interpretation techniques were applied to several sets of flights, belonging to different years from 1956 to 2004. The definition of the shoreline position through time was made by using control lines normal to the coast, and measuring changes in the position of the toes of dunes and cliffs. Following this procedure, errors induced by the fluctuating sea-level were avoided. These kind of measures were restricted to natural coasts, since in urbanized areas dunes and cliffs have been replaced by promenades and other constructions, and urban beaches have experienced changes controlled by human interventions (by-passing, nourishment works, etc.).

4. Guadalquivir estuary

The geomorphologic evolution of the Guadalquivir estuary was recently studied by Rodríguez Ramírez (1996, 1998) and Rodríguez Ramírez *et al.,* (1996). In these papers, the authors distinguished different morphogenic systems and periods of different dynamics.

The Guadalquivir estuary comprises two morphogenic systems: littoral and estuarine (Fig. 2). The littoral system is formed by the various spits and sandy strands that tend to seal off the estuary. On the right bank is the Doñana spit. This comprises the most extensive system of spits, which has grown towards the E and SE. They are partly covered today by active dunes. On the left bank is La Algaida spit, which has grown towards the NNE. The estuarine system comprises the marshes filling the extensive area behind the littoral spits. This filling has taken place gradually as the littoral formations have sealed the estuary. Thus, there is a direct relationship between the littoral formations and the estuarine ones. The marshes include various morphologies, as a result of intense fluvial action.

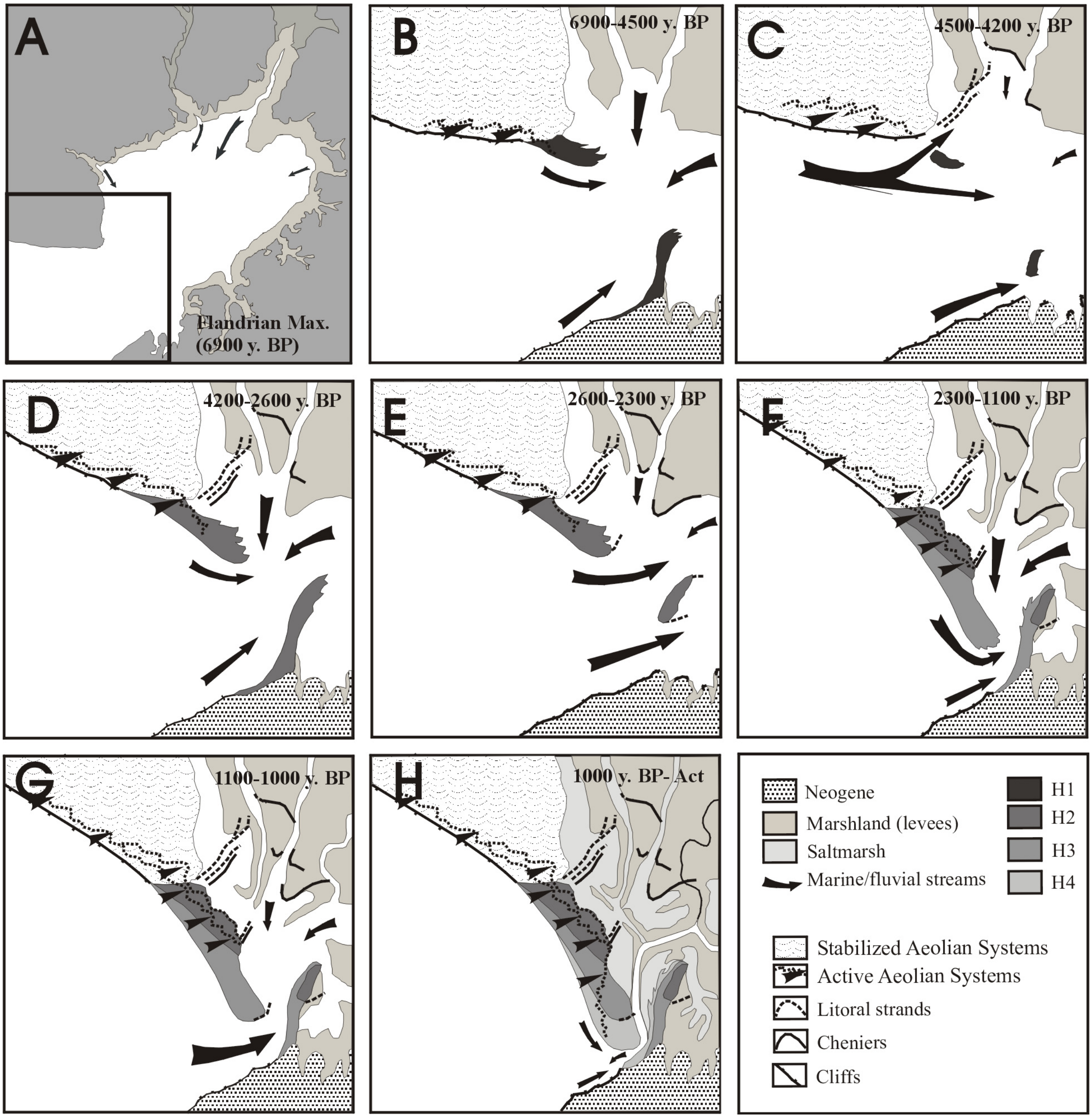

Fig. 2.- Evolutionary sequence of the Guadalquivir outlet area: A. First erosional event, B. Second progradation phase, C. Second erosional event, D. Third progradation phase, E. Third erosional event, F. Fourth progradation phase (Rodríguez Ramírez, 1996).

Fig. 2.- Secuencia evolutiva de la desembocadura del Guadalquivir: A. Primer evento erosivo. B. Segunda fase progradante. C. Segundo evento erosivo. D. Tercera fase progradante. E. Tercer evento erosivo. F. Cuarta fase progradante (Rodríguez Ramírez, 1996).

4.1. Pre-anthropogenic change dynamics

The situation immediately before the large anthropogenic transformations carried out in the Guadalquivir estuary was that of a 140,000 ha estuary, consisting of marshland and a series of coastal spits.

The mapped littoral spit systems constitute four progradation phases (H1, H2, H3 and H4) (Fig. 2). Archaeological evidence and calibrated dating of ^{14}C and aminoacids of fossil shells has helped to establish an absolute chronology. The first is dated between the Flandrian maximum (6,900 yr BP) and 4,500 yr BP; the second, between 4,200-3,900 yr BP and 2,700-2,600 yr BP; the third, between 2,300 yr BP and 1,100 yr BP; and the fourth, between 1,000 yr BP and the present. Successive erosional phases between 4,500-4,200 yr BP, 2,600-2,300 yr BP, and 1,100-1,000 yr BP have occurred, and are represented by cheniers and littoral strandlines in the marshland

(Fig. 2) (Rodríguez Ramírez *et al.,* 1996).

The sedimentary episodes over the last 2000 years has shown a marked alternation between ridges and swales, with an estimated periodicity in the growth of each ridge of 50 years (Rodríguez Ramírez, 1996), accompanied by the development of a considerable aeolian sheet. It seems to have been reactivated more strongly since the 16th century, as shown by the last phases of littoral accretion.

Erosion of the coastal cliffs has been very intense. The marked coastal retreat of El Asperillo cliff is demonstracted by the destruction of 16th century coastal buildings (watch-towers). The retreat at Matalascañas can thus be estimated as 170 m in the last 240 years. The smoothing of this promontory or coastal headland, situated to the west of Doñana, has moved the erosional-sedimentary point of inflection towards the east. The erosive processes have extended towards the root of the ancient littoral spit of Doñana. The rate of retreat has been estimated as 200 m in the last 220 years. The sediment resulting from this erosion has accumulated at the SE end, which has prograded 180 m.

Thus, cycles of higher sedimentation are established, with a slight fall and then stability of the sea level. Littoral barrier construction predominate, with the genesis of extensive intertidal-flats that have reduced the size of the estuaries. The progradational phases isolated the Guadalquivir estuary from the sea, led to a decreased marine influence inland and to the establishment of a predominant continental environment (Fig. 2). The filling of the estuary was helped by the development of small, fingered deltaic bodies (bird-foot type) at the mouths of the main tributaries (Rodríguez Ramírez, *et al.,* 1997). These sedimentary phases were interrupted by rapid rises in sea-level, when the previously constructed littoral barriers were eroded. The cliffs retreated, causing inland migration of dunefields, with frequent overlapping of dune systems and the marine influence within the estuaries increased.

4.2. Post anthropogenic change dynamics

The Guadalquivir estuary has experienced a progressive degradation in the past decades, despite having numerous nature reserves in many of its parts (Reserve of the Biosphere, Doñana National Park and Natural Park of Doñana Surroundings). Its fluvial-tidal dynamics have been essentially altered as a result of the construction of numerous dams in its hydrographical basin, river channelling and other river works.

The construction of dams has reduced the river flow, especially as concerns the large winter floods, when flow can reach over 10000 m^3/s. According to Menanteau (1979), the flow mean of these floods has decreased since 1945 from 5000 m^3/s to 2000 m^3/s.

In the past decades, the new river cut-offs, which have eliminated most of the meanders, and some of the river channels with artificial bunds that have isolated large portions of marshland from river and tidal floods, have altered the tidal wave, which has remained basically in the lower course of the river and increased its range and speed, (Vanney, 1970) (Fig. 3). It now attains 1.35 m/sec at high tides and low tides speed of 0.45 m/sec, with acceleration in the rectilinear sectors of the cut-offs that can reach 48 km/h in the lower section (Vanney, 1970).

Today, longshore drift is becoming stronger, and sedimentation is increasing at the end of Doñana spit. Beach-ridges are being formed with NE orientation, encroaching into the Guadalquivir channel, with a rate of progradation of 375 m, from 1956 to 1996 (9 m/ year) and a decrease in cross-sectional of the fluvial channel (Rodríguez Ramírez, *et al.*, 2003).

In contrast to other estuaries of the Huelva coast, no jetties have been built in the mouth of the Guadalquivir River, but instead there has been a growing urbanization of an important sector of the left margin of its mouth, where the town of Sanlúcar de Barrameda is located. It is precisely in this sector where the highest rates of retrogradation occur (Fig. 3). Also, during the winters of 1994-95 and 1995-96, there was a retrogradation of 20 m of the Punta de Montijo cliffs (Rodríguez Ramírez, 1996).

5. Tinto-Odiel Estuary Mouth

The sedimentary evolution of the Tinto and Odiel estuary mouth was recently studied by Borrego *et al.* (2000) and Morales *et al.* (2004). In these papers, the authors distinguished two periods when different dynamics prevailed separated by the construction of the jetty *Juan Carlos I* and another jetty located at the mouth of a secondary tidal channel in the town of Punta Umbría (Fig. 4). The construction´s objective was to protect the main channel of the estuary, and to prevent sand input from the swash platforms and to maintain the depth of the Huelva harbour. This construction began in 1974 and was completed in 1981. The first dynamic period, previous to this construction, represents the natural conditions, whereas in the latter, the dynamics was modified by human action.

5.1. Pre-anthropogenic change dynamics

Nautical charts from 1829 and 1852 (Fig. 5) reflect the situation of the outer zone of the estuary under natural

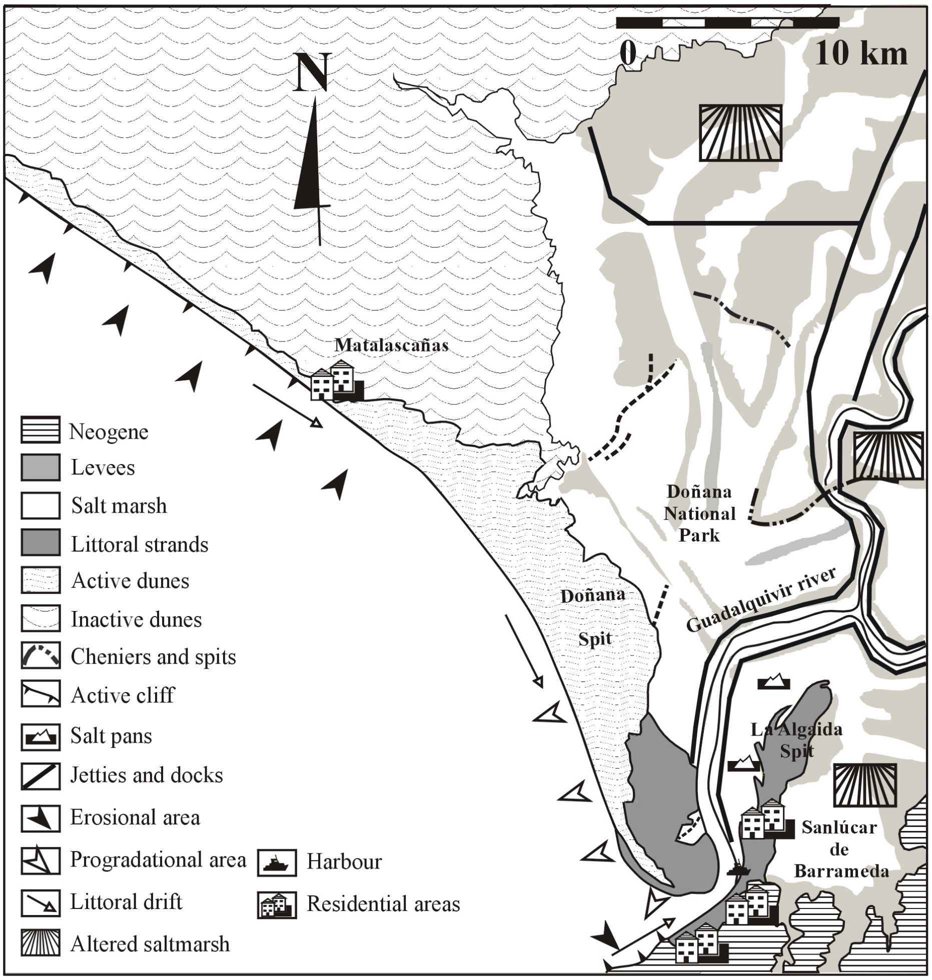

Fig. 3.- Geomorphological synthesis of the Guadalquivir outlet area including the main anthropogenic activity and dynamics.

Fig. 3.- Esquema geomorfológico de la desembocadura del Guadalquivir incluyendo las principales transformaciones antrópicas y su dinámica.

conditions. All of these charts show the presence of a wide shoal in the southern part of Saltés Island that extends parallel to the continental coastline in a southeast direction. The charts show a large number of shallow channels each of which served as entrances to the harbour. The same features can be observed on aerial photographs of 1956 (Fig. 5). This shoal corresponds to an ebb-tidal delta system located at the estuary mouth where the numerous channels can be identified together with main ebb channels and the shoals with their intertidal levees and frontal lobes serving as swash platforms.

The existence of another similar feature in front of the end of Punta Umbría spit is also evident (Fig. 5). This shoal is another ebb-tidal delta system with two or three main ebb channels. A detailed analysis of this photograph shows the presence of curved swash bars on these swash platforms, with ridges oriented in an overall NW-SE position.

In addition, the charts and the aerial photograph (Fig. 5) show a platform topographically more elevated than the ebb-tidal deltas, named "*Bajo del Manto*". It was interpreted by Borrego *et al.* (2000) as a sandy intertidal-flat protected from direct wave action by the Punta Umbría ebb delta system. Over this intertidal flat linguoid and straight crested megaripples, sand waves and beach ridges migrate under high energy wave conditions. The even higher sandy area "Cabezo alto" shows the nucleus of the most recent beach ridge formed at Saltés Island.

5.2. Post anthropogenic change dynamics

The detailed analysis of the maps drawn using aerial photographs from 1977, 1982, 1987, 1991 and 1994 (Fig. 5), allows the analysis of the evolution of the study area after the construction of the Juan Carlos I jetty. This structure reduced the tidal circulation over the ebb-tidal deltas causing the delta system to lose its functionality. On the other hand, the part of the system which remained exposed to the waves was reworked to build an open beach with a shoreface and foreshore with a relatively steep gradient attached to the jetty.

The morphological changes were very rapid in the wave-dominated zone. Nevertheless, the inner zone of the intertidal flat continued functioning under conditions similar as those during the pre-jetty situation because the direction of the refracted waves was not modified. The construction of a second jetty at the apex of the Punta Umbría spit after

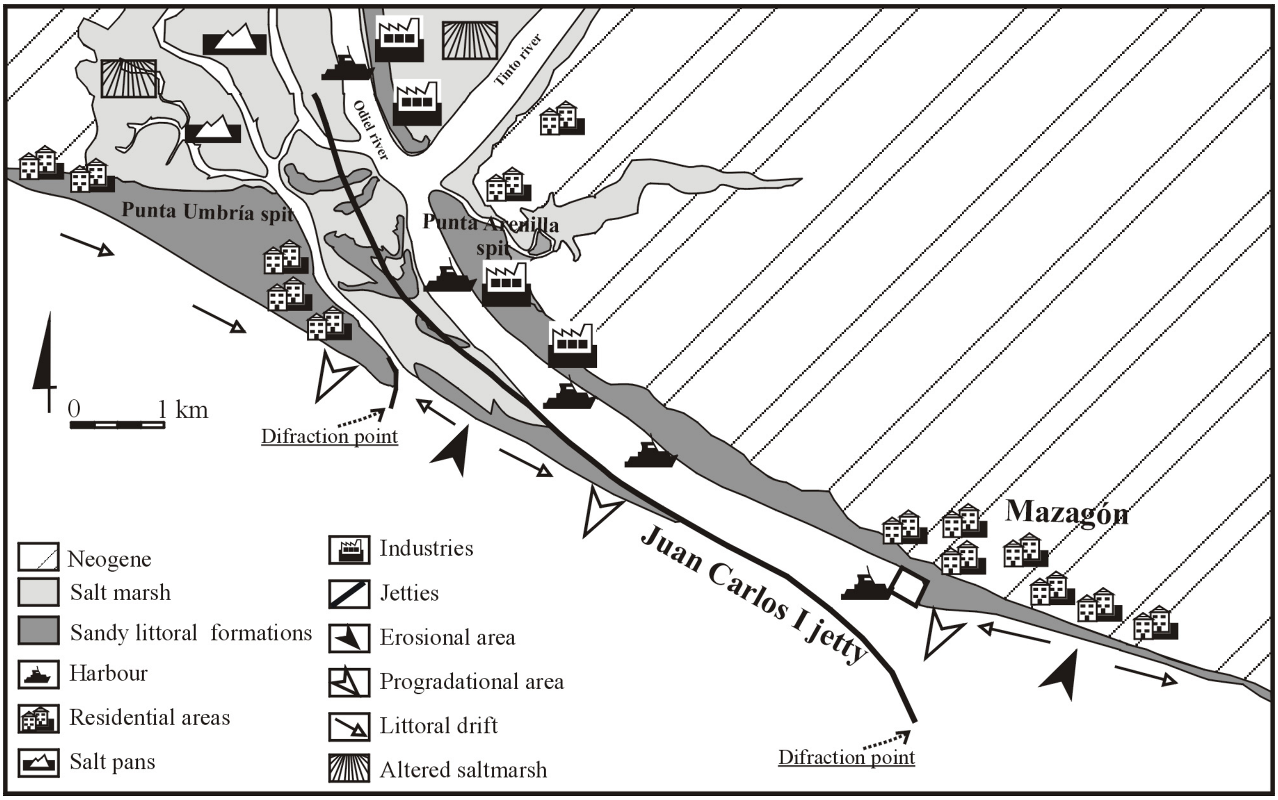

Fig. 4.- Present-day situation of the outer zone of the Tinto-Odiel estuary, including the main anthropogenic activity and dynamics.
Fig 4.- Situación actual de la desembocadura del estuario del Tinto-Odiel incluyendo las principales transformaciones antrópicas y su dinámica.

1984 contributed to a new modification causing the demise of the Punta Umbría ebb-tidal delta system (Fig. 5). This allowed the waves to rework the sand from the ebb-delta to form subtidal sand bars that supplied material to the open beach attached to the Juan Carlos I jetty. The sand input from these bars contributed to the development of a spit that totally isolated the intertidal flat from any wave energy (Fig. 5, 1987, 1991 and 1994). Since that time, the tide has been the only agent acting on the flat, and it has become muddy. 2D type dunes, 3D type dunes and sand ridges no longer migrated over the flat and it is now covered by cohesive muddy sediment.

Stereographic-paired photographs from different years (1956, 1984, 1987, 1991, 1994 and 2000) have been used to analyse the recent coastal changes in Mazagón Beach. The comparison of the coastline over these years (Fig. 6), allowed the calculation of the rates of the progradation and retrogradation. Unfortunately, there is only one flight previous to the construction of the jetty Juan Carlos I (1974 -1977) and it was not possible to make any calculations for the period of natural evolution.

This analysis displays the existence of two areas with different accretionary tendencies (Fig. 6): the first of these areas is located in the sector of the old Sailing Club and was clearly erosional during the whole period studied, with the retrogradation rate increasing since 1987. The second area is located East of the present yachting dock and changed from being erosive before the construction of the jetty Juan Carlos I, to having a high rate of progradation following its construction. There was another clear increase in this rate after the construction of the new yachting dock in 1991-1993 (Fig. 6). This fact suggests the need of a separate field study for these two sectors to analyse their dynamic evolutions.

Topographical profiles (November, 1995 to July, 2002) corroborate that the old Sailing Club area experienced strong erosion, especially during the storms which occurred between December 1995 and February 1996. This represented a loss of 0.71 m^3 per m^2 per year (Muñoz Pérez *et al.*, 2001), but with peaks of sedimentary loss of 1.25 m^3 per m^2 during the storm periods (Morales *et al.,* 2004), which almost double the value of permanent erosion obtained by Muñoz Pérez *et al.* (2001).

In contrast, progradation continued in the yachting harbour area during the same period despite the strongly energetic conditions. This area has experienced a very high progradational rate since the building of the jetties, but especially after the building of the dock. The profiles located in the yachting harbour area show a clear development accretion by an active system of ridge and runnels. The progradation rate was more than 65 meters per year between 1991 and 1994. This eastern erosion-western

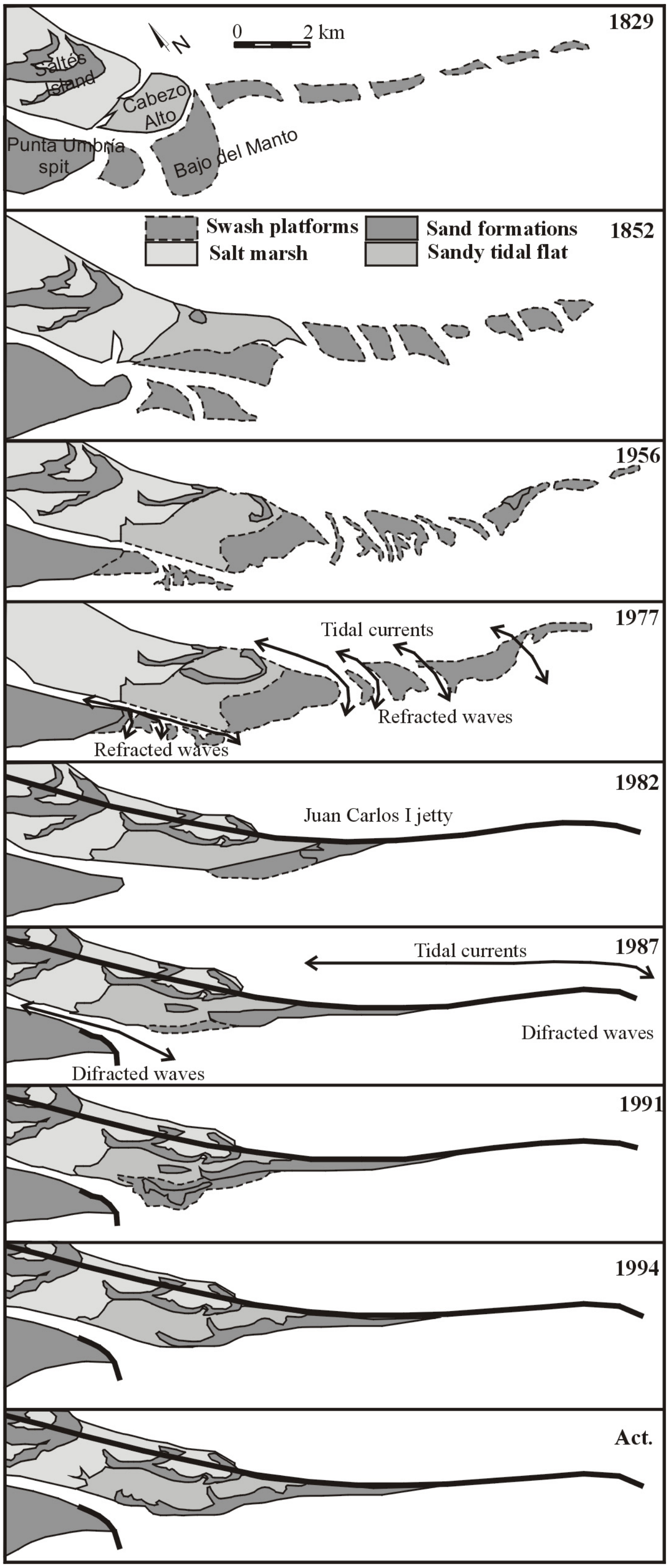

Fig. 5.- Evolutionary sequence of the outer zone of the Tinto-Odiel estuary from 1829 to present (Morales *et al.,* 2004, modified).

Fig. 5.- Secuencia evolutiva de la desembocadura del estuario del Tinto-Odiel desde 1829 al presente (Morales *et al.,* 2004, modificado).

progradation model made the coastline rotate in an anticlockwise sense. Nevertheless, the eroded sand volume in the eastern zone is higher than that of the deposited volume in the western area, because a part of the sand is transported towards the east by the normal west-to east littoral drift. Today, this ratio has decreased because the coastline has extended beyond the front of the dock.

6. Piedras Estuary

Unlike, as in the previous described estuaries, here there has been no construction of jetties in the mouth of the Piedras River. The main transformations in the evolution of this coastal system have been linked to the regulation of the river basin since 1971, when a dam were built on the river and the modification of the volumes of tidal drainage by commercial fisheries in 1980.

On the one hand, the construction of another dam just in the fluvio-estuarine zone in 1972 contributed to the modification of the previous coastal dynamics of this system and to the almost complete removal of the river contribution (Borrego *et al.*, 1989). Also, on the other hand, the damming of large areas of marshland for fish-farming has contributed to a sharp decrease of the tidal prism.

6.1. Pre-anthropogenic change dynamics

The Piedras River estuary developed a long coastal spit at its mouth as a result of the fusion of some older barrier islands (Fig. 7) due to the closure of tidal inlets (Morales *et al.,* 2001). This spit has developed parallel to the coast in an East-West direction over approximately 15 km, with a mean apical growth rate of 32 m/year (Borrego *et al.,* 1993). This was an extremely high growth rate for natural conditions. Also, these was a displacement together with an extension of the large beach, opposite the tip of the spit, towards the La Bota sector. This apical growth of the spit occured due to a rapid process of swash bar welding, helped by the migration of a system of tidal-deltas located in its frontal area. This has been interpreted as the system's response to the progressive reduction of the tidal prism caused by sedimentary infilling of marshes inland.

6.2. Post-anthropogenic change dynamics

The present fluvial discharge of the Piedras River can be considered as zero since the construction of two dams in its main channel, the Piedras dam and the Los Machos dam, which are located within the limit of tidal influence mark the boundary of the river's fluvial system. Both dams

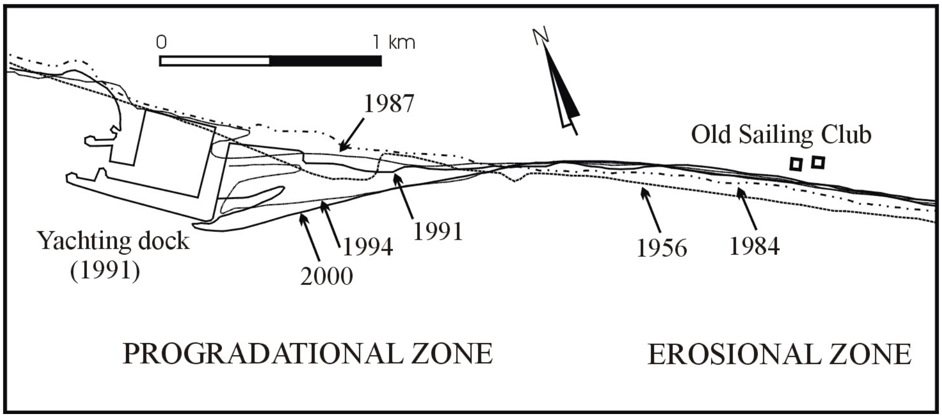

Fig. 6.- Recent coastline changes in Mazagón Beach due to the Juan Carlos I jetty (Morales *et al.,* 2004, modified).

Fig. 6.- Cambios recientes en la playa de Mazagón debido al espigón Juan Carlos I (Morales *et al.,* 2004, modificado).

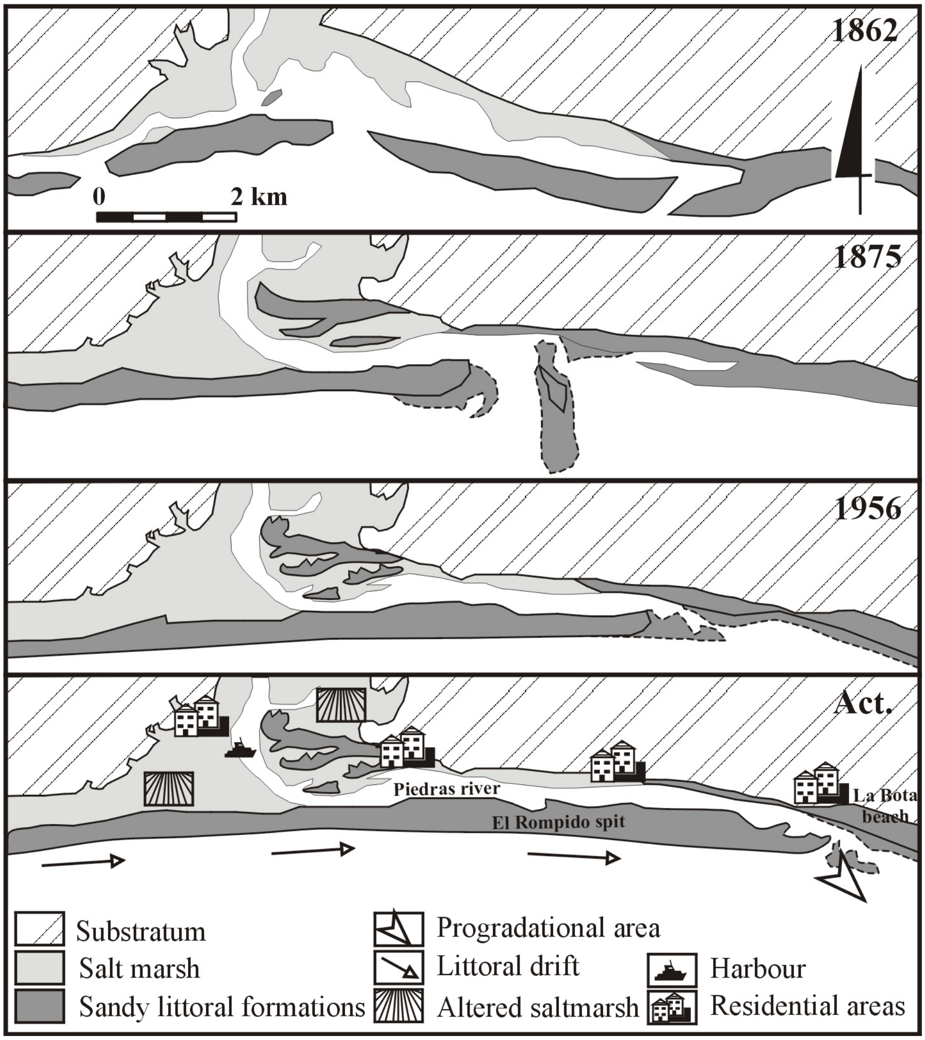

Fig. 7.- Recent coastal changes of the Piedras estuary from 1862 to 1956 (Morales *et al.*, 2001), including the present situation with the main anthropogenic activity and dynamics.

Fig. 7.- Cambios costeros recientes en el estuario del río Piedras desde 1862 a 1956 (Morales *et al.*, 2001), incluyendo la situación actual con las principales transformaciones antrópicas y su dinámica.

are hazardous as they are built upon loose materials.

Before these constructions, the fluvial discharge was notably seasonal, approximately 75 x 10^6 m^3/year, occured mainly during the wet months, and were practically zero during the summer. The average flow was estimated by Borrego *et al.* (1995) as less than 11 m^3/s, but during more important floods, it exceeded 35 m^3/s. These floods only occured once in four or five years, but could incorporate large amounts of sand that was trapped by cohesive sediments deposited during dry periods.

The marshland of the Piedras River has preserved its natural conditions until recently (approximately until the 1980's). During those years, a significant process of change has caused mainly due to the implementation of

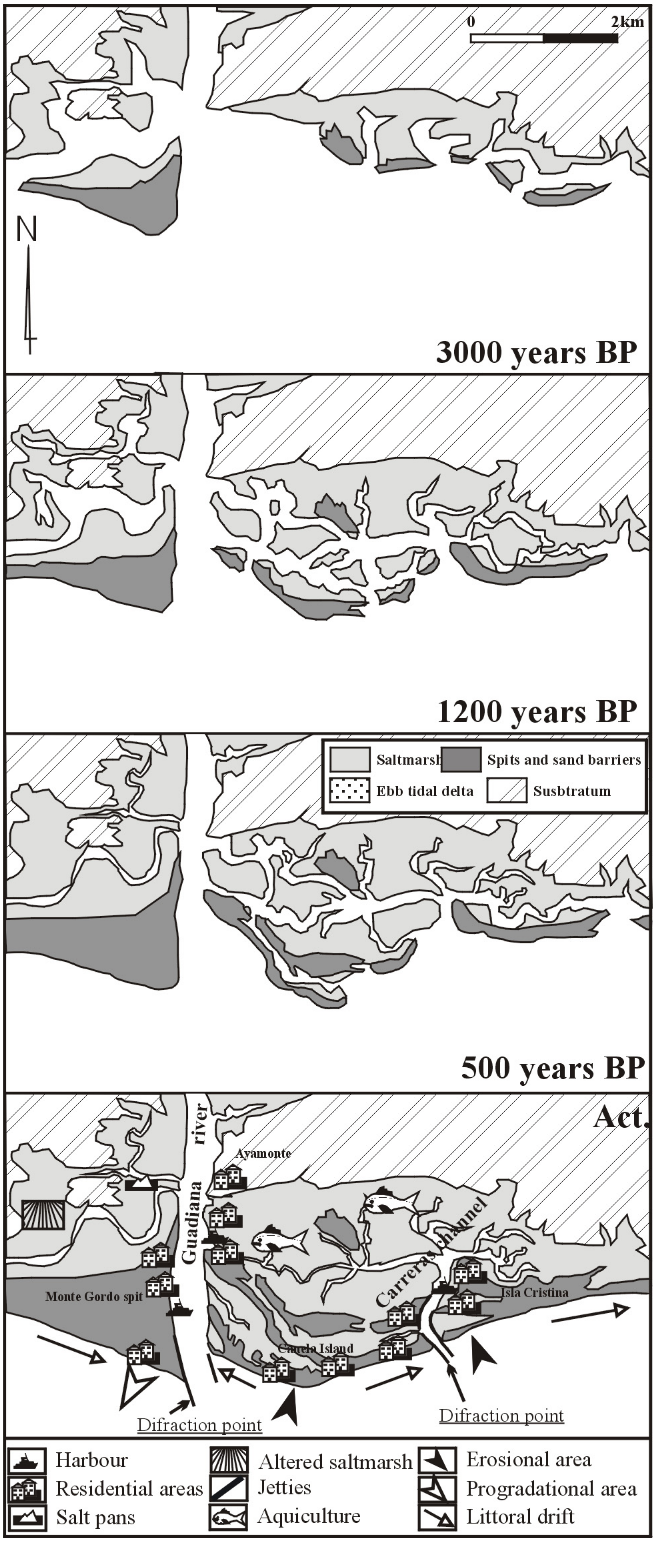

Fig. 8.- Coastal evolution of the Guadiana estuary and Carreras tidal channel from 3000 years BP to 500 years BP (Morales *et al.,* 1997); also showing the present situation with the main anthropogenic activity and dynamics.

Fig. 8.- Evolución costera del estuario del Guadiana y del caño Carreras desde los 3000 años BP a los 500 años BP (Morales *et al.,* 1997), incluyendo la situación actual con las principales transformaciones antrópicas y su dinámica.

aquiculture since 1974. These activities and their related facilities were progressively abandoned after 1987, but a reactivation began in the early 90's.

The restriction of tidal incursión from large marshland areas has produced a decrease in tidal currents in the estuary mouth due to the decreased tidal prism. Lower currents have caused morphological changes in the tidal deltas at its mouth, which at present are developing front lobes closer to the shoreline as well as shallower tidal-channels as a result of the greater influence of swell in the swell-tide balance. Apart from these morphological changes, the lack of tidal influence has caused an increased mobility of these channels and a rising apical growth rhythms of the spit reaching values that exceed 63 m/year (Borrego *et al.*, 1995). Between 1956-1996 seven beach ridges were formed, with a rate of progradation of 945 m (23,6 m/ year). An interesting correlation was found between the storm records and the progradation (Rodríguez Ramírez, *et al.,* 2003).

7. Guadiana River Delta

The sedimentary evolution of the Guadiana river delta was recently studied by Morales *et al.* (1995 and 1997). In these papers, the authors distinguished two periods of differing dynamics divided by the construction of four jetties: two at the mouth of the Guadiana main channel and two more at the mouth of a secondary feeder tidal channel (Carreras channel). The objective of these jetties was the stabilization of a very mobile channel. This construction was completed in 1979. The dynamics of the first period, previous to this construction, represents natural conditions, whereas the latter stage signified dynamics of the stimation after it was modified by human action

7.1. Pre-anthropogenic change dynamics

The present morphology of the mouth of the Guadiana River system is the result of its evolution during the Holocene. Since the post-Flandrian stabilization of the sea level, about 2490 x 10^6 m^3 of sediment have accumulated on an area of 10.5 km x 7 km (73.5 km^2), indicating a mean accumulation rate of 500 x 10^3 m/yr (Morales, 1995). This mass of sediment material has contributed to the filling of the bay in the most southern portion of the system, causing coastal progradation to take place and the formation of a wave-dominated delta.

The earliest progradation occurred in a different way on either side of the mouth of the estuary as shown on the paleogeographical reconstruction elaborated with archeological data (Fig. 8). A transverse growth of the Monte

Gordo Beach spit occured on the western side, whilst on the east, the progradation formed as new barrier islands from active sandbars. This diagram also shows that on the eastern margin a progressive evolution from a typical tide-dominated coast morphology (sensu Hayes, 1979) to a mixed-energy coast dominated by waves. The development of this morphological change is attributed to a progressive increase wave energy on this side (Morales, 1997). This was only possible if aggradation occurred in the entire eastern part of the bay to generate a large shallow shelf which slowly dissipated the wave energy before it arrived at the first barrier island line. It is also possible that the initial aggradation of the barrier was produced on a previously erosive shelf cut in Pliocene materials, in a similar way as the Keys that close Sarasota Bay in the Gulf Coast of Florida (Davis *et al.*, 1989).

The historical evolution in the last 200 years (Fig. 9) determined from historical maps allows a detailed reconstruction to be made of the most recent barrier-islands and spits that are situated near to the Guadiana's main estuarine channel. The given flood- and ebb-tidal The current directions of the flood-and ebb-tide together with the wave activity resulted in the development of an asymmetrical delta, with a very large western swash-shelf in the form of the Monte Gordo spit extension; The causes of the asymmetry are similar to the D-model of Sha (1989) for ebb-tidal deltas. Under normal conditions, waves move and become larger toward the east on that shelf (Fig. 9, the 1793 situation). Consequently, the main channel established a connection with the estuarine channel, and migrated north-eastward. However, during extreme fluvial discharges, new channels could be opened, to separate the western swash platform from Monte Gordo Beach (Fig. 9, 1838). After these events, the main channel became orientated more perpendicular to the coast so the old main ebb-channel now functions as a marginal flood-channel. Swash-bar migration on the levée became faster and the entire levée migrated until it choked the secondary flood-channel (Fig. 9, 1875). As the secondary channel closed, the swash bar was able to build a new spit, establishing a lagoonal, intertidal flat conditions on the landward side. There the closing of the channel made the lower area –corresponding to the old secondary flood channel– work as an incipient creek network (Fig. 9, 1915, 1938 and 1959). An ebb-tidal delta started to grow in the front of the new spit with the subsequent development of a new swash platform, associated with the Monte Gordo spit, thus completing a progradation cycle. This progradation is shown as a drumstick barrier island (Isla Cristina: Fig. 10) formed by accretion of small spits to the original barrier island with the sediment supply from a large ebb-tidal delta associated with the feeder inlet. The accretion of these small spits on the island gave rise to instability of the feeder inlet position.

7.2. Post-anthropogenic change dynamics

In 1974, the construction of jetties artificially stabilized the channel perpendicular to the coast (Fig. 9, 1982), preserving what had previously developed in a natural way as the result of fluvial floods events. Since then, disconnection between the levee-swash platform and the Monte Gordo spit has allowed a northward migration of the old levee by about 700 m (Fig. 9, 1994). This indicates a migration rate of less than 60 m/yr and a change in wave conditions as the ebb currents stopped flowing directly over this platform area. Until now, no new barrier-islands have developed as a result of progradation east of the Carreras feeder channel.

The unstable position of the Isla Cristina feeder-inlet resulted in the construction of two jetties to stabilize the channel. This artificial construction modified the wave refraction, contributing to new spit growth and to the removal of the ebb-tidal delta (Fig. 10, 1994). Around 1850, "La Tuta" inlet, the boundary of the transgressive eastern end of the island, was naturally filled because the currents lost energy due to the decrease of the tidal prism, together with the role of storms at this point. Washover fans also contributed to the filling of the inlet and the former La Tuta channel. Thus, the island became attached to the mainland as it is today, but problems of coastal erosion continue in this area. The modern evolution of Isla Cristina (Fig. 10) is somewhat analogous to that of the Algarve barrier islands to the west (Bettencourt, 1988; Pilkey *et al.*, 1989).

6. The Future of the Coast

The threats to the Huelva coast, as in the rest of the world, in the near future are the cause of great concern. The numerous coastal infrastructures, especially jetties, have substantially changed the existing erosive-sedimentary dynamics, hindering the transfer of sediments from east to west, and affecting the beaches on the other side of the jetties. The impact on the Huelva beaches, with such seasonal characteristics, is their progressive loss, as they do not recover from the erosive winter processes (Isla Canela –Guadiana–, Mazagón beach –Tinto-Odiel–).

However, the biggest problem to be faced is that one the effect of climate change, which will result in an increase in the sea level worldwide. In the Gulf of Cadiz the increase was of the order of 20 cm from 1967 to 1998,

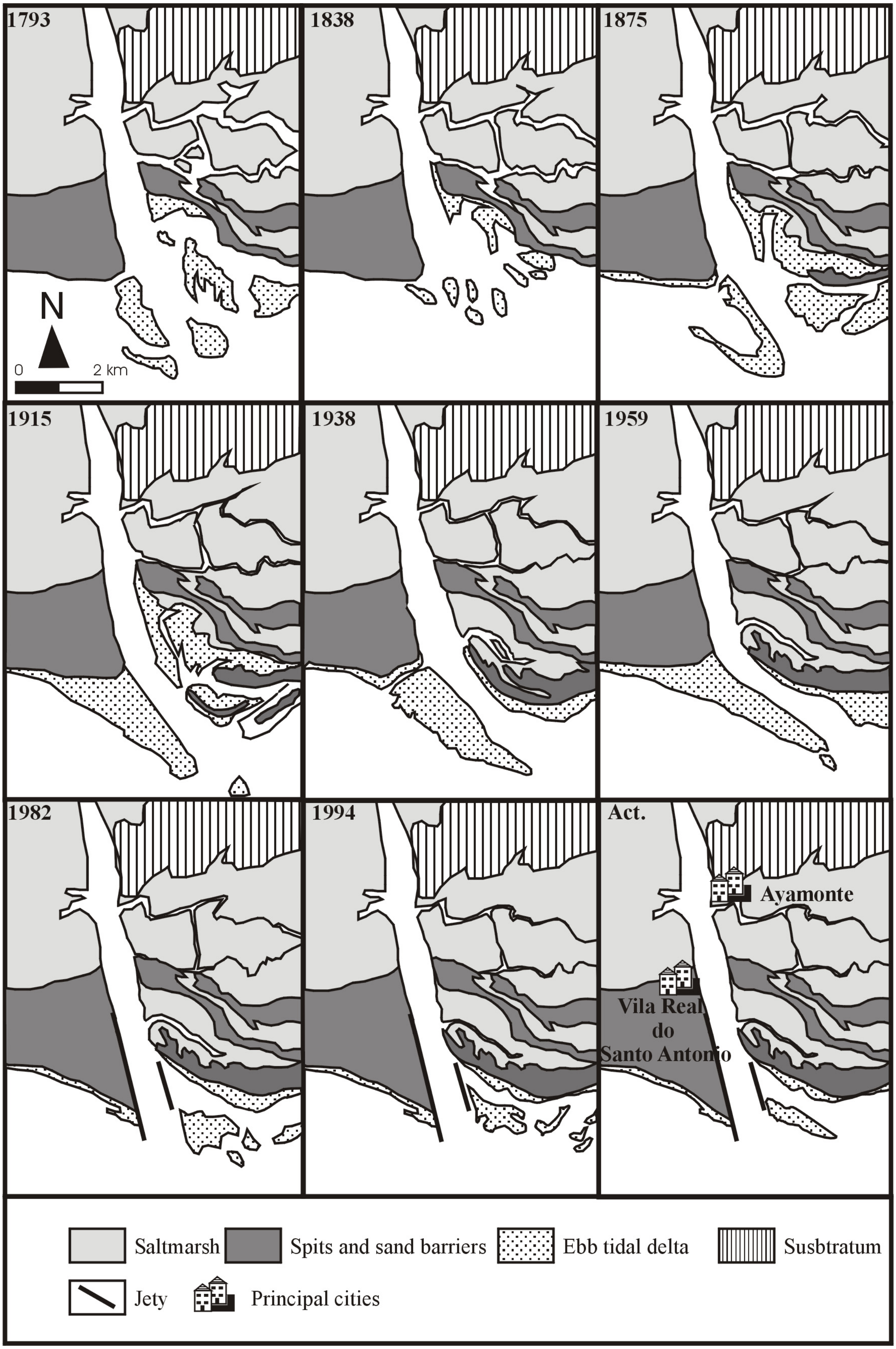

Fig. 9.- Coastal evolution of the Guadiana estuary from 1793 to present (Morales *et al.,* 1997, modified).
Fig. 9.- Evolución costera del estuario del Guadiana desde 1793 al presente (Morales *et al.,* 1997, modificado).

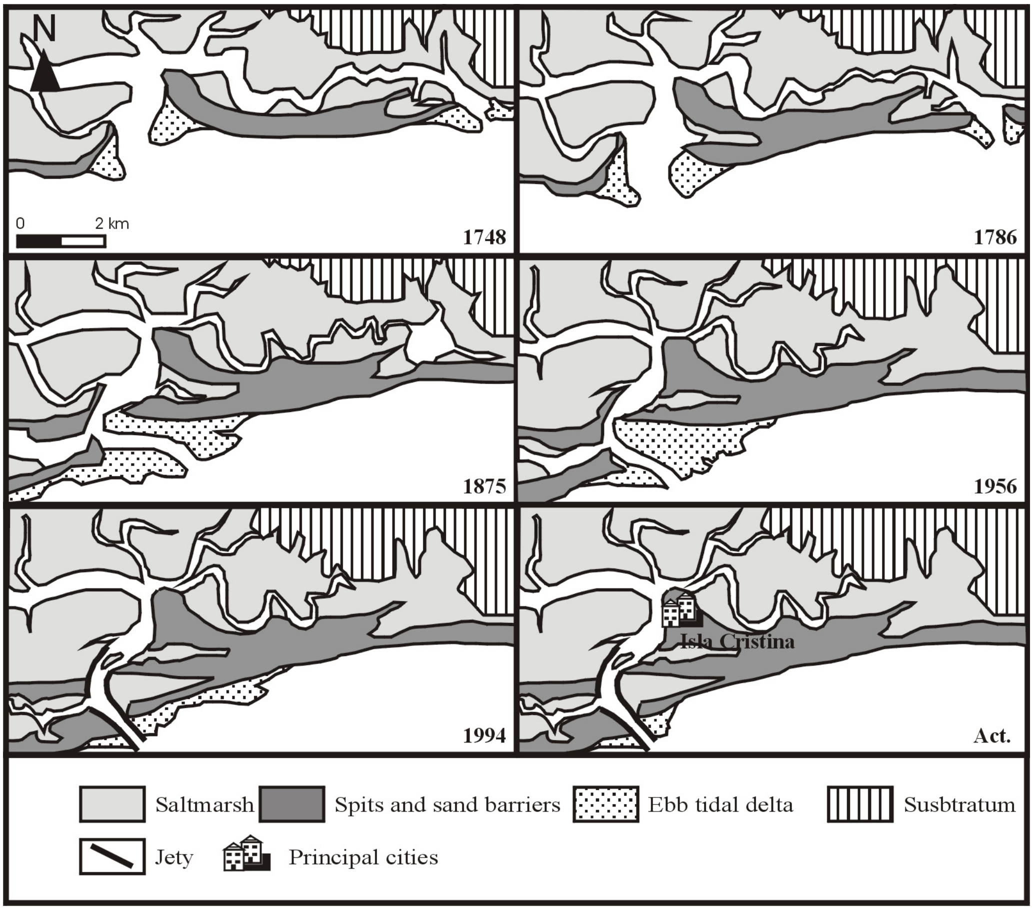

Fig. 10.- Coastal evolution of the Carreras tidal channel sector from 1748 to present (Morales *et al.,* 1997, modified).
Fig. 10.- Evolución costera del entorno del caño Carreras desde 1748 al presente (Morales *et al.,* 1997, modificado).

with an annual rise of 0.6 cm (Fig. 11). This will give a rise in sea level of the order of 30 cm, with respect to that of the present level, by 2050.

As a result, a general retrogradation of the shoreline will occur: coastal cities, harbours and beaches will be seriously affected by this sea level increase. Most coastal jetties will become useless. Erosion will be increased in those areas with a higher coastal retrogradation. Besides, the poorly cohesive nature geological formations of the cliffs of the Huelva coast, are likely to suffer very intense erosion by winter storms.

The coast of Huelva has a low slope, so a rise of sea level can result in a substantial retreat. Thus, it would be advisable to recover control of the beaches into the public domain and to regenerate them. The first of these measures is the correct, path to follow and is no more than the accomplishment of the Spanish Coastal Act, of 1988 which delimited two zones in littoral areas: a) a protection zone (100 m landward), with prohibition of both residential and/or recreational constructions; and b) zone of influence (500 m landward), with restriction of the building density. Beach regeneration is a continuous and useless expensive process and more natural methods should be applied to secure the future of the beaches.

Apart from these morphodynamic aspects, pollution is an especially serious problem in the coast of Huelva. Heavy chemical industry, refineries, coal-fired power stations, etc., whose emissions affect the climate, the water quality and the sediments occur on the margins of the Tinto-Odiel estuary (e.g. Borrego *et al.*, 2004 or López-González *et al.*, 2006) .

At present, the Huelva littoral is subjected to increasing pressure due to tourism and other recreational demands. Consequently, a strategic plan is necessary to control the exploitation of coastal resources and rapid development of infrastructures. This integral management must include the evaluation of the sedimentary effects produced by the main jetties, short-term periodic analyses of beach-nearshore profiles of the main beaches, with special attention being given to significant changes occurring during energetic events (storms, tsunamis). This is the first approach to a long-term coastal development, ie examining the roles of waves, tides and sediments in coastal dynamics. As Carter (1988) pointed out, coastal strategies, including a future redistribution of the littoral space. The establishment of protection zones, demoli-

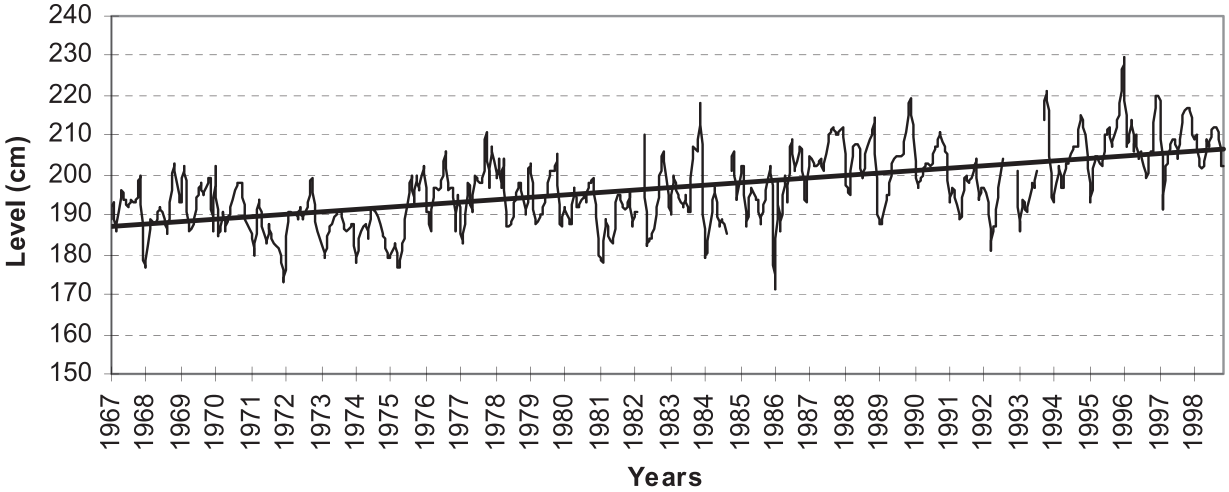

Fig. 11.- Sea level evolution in the Gulf of Cadiz from 1967 to 1998 (Instituto Español de Oceanografía).

Fig. 11.- Evolución del nivel del mar en el Golfo de Cádiz desde 1967 a 1998 (datos aportados por el Instituto Español de Oceanografía).

tion of shorefront residences, relocation of both public infrastructures and private homes are very necessary.

7. Conclusions

At the Huelva coast, human activity has directly modified the supply of sediment and coastal processes. The sedimentary balance has been interrupted by the construction of jetties, docks, harbours, residential areas, hotels, etc. These infrastructures have modified the sedimentary by-passing produced by an active west-to east littoral drift. The jetties constitute a barrier to sand circulation, producing a deficit in the sand budget of the systems located east of each construction, and this is the main cause of beach erosion. Also, they have altered the action of tides on the ebb-tidal delta systems which are located in front of the main estuarine channels. Therefore, the wave action became the main agent acting on the deltaic sand, bodies which become totally reworked to construct new beaches attached to the jetties. The jetties have modified the wave refraction, and induced a diffraction pattern, in the jetty's apical end. This process generates trains of divergent waves that erode the opposite margin of the jetty, with erosional effects on urban housing (Mazagón, Isla Canela). This erosion is extremely high during storms, hindering the natural beach restoration. All these effects will be increased with the progressive sea level rise, which will result in greater energy of the erosive events, with substantial losses of the beach sand.

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