SHORELINE CHANGE PATTERNS IN SANDY COASTS. A CASE STUDY IN SW SPAIN

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Abstract

Coastal changes on sandy shorelines are continuous and occur at diverse spatial and temporal scales. Gaining knowledge on beach change processes increases our capability to manage risks affecting the increasing population living in coastal areas, especially shoreline erosion. Processes and factors involved in medium- and short-term beach changes depend on the morphological and dynamic characteristics of the coast. In this work, the decadal behaviour of 58 sandy beaches along the 150 km long South-Atlantic coast of Spain, between Guadalquivir river mouth and the Strait of Gibraltar, is analysed in order to investigate the relationships between shoreline change patterns and the diverse morphological and dynamic factors controlling beach evolution in the area. For this purpose, georectified aerial photographs spanning the period 1956-2008 were compared in a GIS environment to calculate rates of shoreline change. Short-term evolution of beach profiles was also analysed in selected areas of interest.

Results show that the study area exhibits a great variety of shoreline evolution trends, with prevailing erosion in the northern and central sectors and stability or even accretion in the southern sector. In general, sediment availability is the main factor determining coastal erodibility in the area, largely conditioned by the reduction in fluvial sediment supply caused by river basin regulation. Nearshore bathymetry also has a great significance, as it controls wave refraction-diffraction patterns and wave energy concentration on certain zones. Human interventions on the coast also represent a major influence on beach erodibility in the study area. Severe detrimental effects are caused at certain points by shore-normal engineering structures blocking longshore drift. Additionally extensive urban development in backbeach environments has a significant influence on sediment budget at certain areas.

On the basis of these results, a morphological and evolutive classification of sandy beaches is proposed, taking into account the way beach morphology influences erosive/accretionary processes. Rectilinear beaches and enclosed beaches typically show dynamic equilibrium or even accretion trends, whereas reef-supported beaches tend to be dominated by erosion. Headland-bay beaches show complex evolution patterns greatly influenced by local conditions, such as specific shoaling processes or local winds. This classification is useful not only in forecasting general shoreline behaviour in the near future, but also in selecting the most adequate type of intervention when managing retreating coasts.

Keywords

Beach changes; beach morphology; coastal erosion; aerial photographs; Gulf of Cadiz

1. Introduction

Sandy coasts are extremely dynamic geomorphic systems where continuous changes occur at diverse spatial and temporal scales. In the short term, coastal changes are related to fluctuations in wave energy and associated processes. On a long-term scale (centuries, millennia), coastal variability is mostly conditioned by relative oscillations of sea level and river sediment discharge, both mainly driven by climatic changes (Cowell and Thom, 1994; Paskoff and Clus-Auby, 2007). However, on an intermediate time scale (decades) factors influencing coastline changes are more complex and interrelated, including both natural and anthropogenic causes. In this regard, Komar (2000) emphasized the role of sediment budget in coastal stability, particularly influenced by river watershed changes, river water use, river damming, jetties and breakwaters and shore protection structures, among others. At this scale shoreline and beach planform often evolve quite rapidly in space and time. Causes for these variations are not always evident, thus rendering it difficult to develop predictions of future shoreline behaviour. Gaining knowledge on beach change at the intermediate time scale would increase our capability to manage risks affecting the increasing population living in coastal areas, especially those risks acting on a decadal basis such as medium-term shoreline erosion.

In fact, over the last decades coastal erosion is becoming a problem of increasing magnitude in the sandy shores of Spain (Sanjaume et al., 1996; Ojeda et al., 2002). Interventions aimed at addressing shoreline retreat processes are being included in coastal management plans in those areas where the “sun & sand” tourism model comes into conflict with a generally slow but continuous loss of beach sand. In this respect, long enough datasets of morphological historical records are necessary to investigate local and regional causes for coastal erosion, identify shoreline trends, detect types of coastal change and define sectors where coastline behaviour can be considered homogeneous over time (Crowell et al., 2005).

On embayed and pocket beaches affected by an active longshore current, patterns of shoreline change can in some cases be successfully predicted when triggered by human interventions on beach planform (e.g. construction of jetties). In these cases different numerical models can be applied with fairly good results (see Komar, 1998 for a synthesis). However, predictions on natural shores are much more difficult, due to the simultaneous occurrence of factors whose variability is not well known. One of these factors influencing medium-term behaviour of natural beaches is geological framework. Beach boundaries, both emerged and submerged, exert a primary control on wave shoaling processes, refraction-diffraction processes and efficiency of longshore drift. Geological control influences every beach in a different manner, and can be responsible for significant deviations from predicted beach behaviour when applying traditional morphodynamic parameters (Jackson and Cooper, 2009). Although quantitative studies on recent shoreline changes and future extrapolations are relatively frequent (e.g. Dolan et al., 1991; Crowell et al., 1993; Guillén et al., 1999), literature about the role of geological controls on medium-term coastline behaviour is far less common (Riggs et al., 1995; Jackson et al., 2005; Lentz and Hapke, 2011).

In this work, the decadal evolution of sandy shores along the 150 km long South-Atlantic coast of Spain, between the Guadalquivir river mouth and the Strait of Gibraltar (covering the Atlantic side of the Cádiz province), is analysed in order to investigate the relationships between shoreline change patterns and the diverse morphological and dynamic aspects of the study area. The main objective is to gain a better understanding of the different factors that control erosion/accretion processes and evolution of beaches, by classifying beaches according to their characteristics and shoreline behaviour. This would help in the design of medium-term prediction models of shoreline change, ultimately contributing to a better assessment of hazards related to the use and evolution of coastal zones.

The case study used provides an ideal scenario for addressing the above issues by analysing factors influencing coastal evolution. The northern half of Cadiz coast is constituted by mesotidal, long rectilinear sandy shores, many of them highly developed, and close to major river mouths responsible for sediment supply to this coast. The southern half is represented by a microtidal, indented rocky coast with numerous small o medium-sized embayments, mainly natural and far from any significant sediment source.

Shoreline changes in the study zone are assessed by means of georectified aerial photographs from the period 1956-2008, along with the topographic monitoring of beach profiles in selected areas of interest. A simple classification of the sandy shore types and associated evolutive trends existing in the area is performed, which helps to understand the way coastal morphology influences erosion/accretion processes. It must be noted that cliffed shores have not been included in this work unless fronted by a beach; in these cases only beach changes have been analysed (for cliff evolution patterns in the study area, see Del Río and Gracia, 2009a, 2009b).

2. Study area

The Atlantic coast of Cadiz province extends along 150 km of the Gulf of Cadiz shore, between the Guadalquivir river estuary and the Strait of Gibraltar (Fig. 1). General coastal orientation is NW-SE with several W-E-oriented traits, so long linear sectors alternate with embayments.

APPROXIMATE POSITION OF FIGURE 1

As a result of the geological framework of the study zone, the coast shows contrasting topography and morphology in the areas located north and south of Cape Trafalgar (Fig. 1). The Northern sector belongs to the end of the Guadalquivir Neogene Basin and is composed of soft, sub-horizontal sediments. This gives rise to a generally linear, low coast with several wide embayments, controlled by Plio-Quaternary faults (Benavente et al., 2005a). Long sandy beaches and sandspits prevail, enclosing salt marsh areas like the Bay of Cadiz. Guadalquivir river, the major watercourse in this coast, flows in this sector (Fig. 1). It is considered to be the main source of sediments to the eastern Gulf of Cadiz, although river discharge has been severely reduced since the 1960s-70s due to dam construction on its basin (Benavente et al., 2005a). The second river flowing into the study area is the Guadalete river, whose mouth is located into the Bay of Cadiz (Fig. 1); also here several dams have been built in the last decades.

The Southern sector of Cadiz province belongs to the Betic Ranges, showing areas of moderate relief on Paleogene and Neogene detritic and calcareous units that were faulted and folded during Mio-Pliocene times. As a consequence, it is characterized by a young, indented coastline, with alternating cliffs and headland-bay beaches controlled by neotectonic features (Silva et al., 2006). Several minor watercourses flow into this coastal zone, the most important being the Barbate river (Fig. 1).

Coastal setting determines prevailing winds in the study area to blow from East-SE *(Levante)* and West-SW *(Poniente)* directions. Warm and dry *Levante* winds blow from the Mediterranean Sea, with high frequency and velocity, especially near the Strait of Gibraltar. These characteristics control the strong influence of easterly winds in aeolian sediment transport in the study area; however, the importance of *Levante* as wave-generating wind is greatly reduced by its short fetch (Gracia et al., 2006). On the other hand, humid *Poniente* winds have a lower influence on aeolian transport, but due to the long fetch they reach great significance in wave generation, especially during winter storm conditions (Benavente et al., 2005a).

Both sea and swell waves generally approach the coast from the West, although SW waves usually achieve greater importance during storms (Del Río et al., 2012). Highest waves appear in winter associated to Atlantic low pressure systems, when they can reach significant heights of up to 4 m. However, over 70% of annual waves are less than 1 m high, so Cadiz littoral can be classified as a low-energy coast (Benavente et al., 2000). General wave conditions slightly shift southwards of Cape Trafalgar, due to changes in coastal orientation and to the higher relevance of *Levante* winds. Consequently, near the Strait of Gibraltar SE waves achieve greater importance, and *Poniente* waves show relatively lower frequency and height. Longshore drift in the study area generally flows in a SE direction because of the prevalence of westerly waves. In the southern Cadiz coast, reduced westerly waves, lower sediment supply and the presence of headlands cause an important decrease in the efficiency of the longshore component of sediment transport by waves.

Tides in the study area are of semidiurnal type, and tidal range gradually diminishes towards the Strait of Gibraltar. The Northern and central sectors are mesotidal coasts according to Davies (1964), with a MSTR of 2.96 in Cadiz city (Benavente et al., 2007). From Cape Trafalgar southwards, the narrowing of the continental shelf (Fig. 1) and the proximity of the Mediterranean Sea produce a sharp reduction in tidal range, so MSTR decreases from 2.30 m in Barbate to 1.22 m in Tarifa (Benavente et al., 2007); therefore, the Southern sector of the coast is a microtidal area according to Davies (1964).

3. Methods

Medium-term beach changes in the study area were assessed by means of 10 sets of aerial photographs and orthophotographs spanning between 1956 and 2008, at scales from 1:15000 to 1:33000 (Table 1). Due to the great extent of the study area, spatial coverage of each photogrammetric flight was not complete, so a total of 6 sets from different dates were analyzed on each coastal sector in order to use homogeneous sources of information. The nearly 300 photographs available were examined through stereoscopic photointerpretation, digital photogrammetry and GIS software, with the aim of obtaining high-accuracy shoreline change data.

APPROXIMATE POSITION OF TABLE 1

The two sets of orthophotographs were directly used as input for coastal change calculations. As for the paper print photographs, they were scanned at high resolution and georeferenced in order to provide a unique geographical reference system that enabled photograph overlapping and thus coastal change measurements. Third-grade polynomic correction with two-dimensional ground control points (GCPs) was used for photo georeferencing in ESRI® ArcGIS 9.3™ software. GCPs were carefully chosen attending to criteria established by authors like Moore (2000) or Hughes et al. (2006). Around 20 GCPs were identified on each photograph, evenly distributed across the whole photograph, and mostly located on man-made landscape features. Average Root

Mean Square Error (RMSE) for the GCPs was 0.48. After several accuracy tests, image resampling was performed by bilinear interpolation. Due to the relatively low relief of beach areas, the georeferencing process resulted in a geometrical correction of most distortions inherent to aerial photographs (Mount et al., 2003; Hughes et al., 2006).

A key issue regarding the monitoring of coastal changes is the selection of an adequate feature that can serve as a shoreline indicator or proxy, so that it properly reflects real shoreline position and evolution (Moore, 2000; Boak and Turner, 2005). In this work the high-water line (HWL) and the dune foot were used as shoreline proxies. The HWL constitutes the most widely used shoreline proxy (Boak and Turner, 2005), and is usually considered equivalent to the last high tide mark or the wet/dry line identifiable on beach sand on the photographs (Crowell et al., 1997). Despite its limitations regarding short-term variability, it is generally deemed as a valid indicator of shoreline position (Gorman et al., 1998), and so it was used along the whole Atlantic coast of Cadiz. At coastal traits where dunes are present, the dune foot (considered as the contact line between the backshore and the foredune) was also chosen as shoreline proxy, with the aim of using an indicator that was completely independent of meteorological conditions, waves, tides and changing beach profile shape (Moore and Griggs, 2002).

The position of shoreline proxies was analysed in 58 beaches along the study area, with lengths ranging between 200 m and 6,000 m. The only beaches not included in the study were the intertidal beaches backed by a cliff or an artificial structure (e.g. a seawall or breakwater), where no valid proxies exist for assessing beach behaviour, since they are completely covered by water in high tide and no dunes are present; these areas and the plunging cliffs without beach at their toe represent about 9% of the total length of the study area.

After identifying the position of the shoreline proxies on each photograph, they were accurately digitized on ArcGIS 9.3, with the help of a mirror stereoscope at some points. Then DSAS 3.2 extension for ArcGIS, developed by the USGS (Thieler et al., 2005), was used to calculate coastline changes. Shore-normal transepts were drawn 50 m apart on the shorelines along the whole study area, and rates of shoreline change between 1956 and 2008 were computed on each transept by linear regression technique between the different dates (Dolan et al., 1991; Genz et al., 2007).

At certain points of interest also short-term variations in beach morphology were evaluated. For this purpose, a seasonal monitoring of 22 beach profiles located at representative coastal sectors was performed. Beach surveys were carried out by means of a total station in February and September-October between the years 2000-2006, with the purpose of recording seasonal beach changes. Additionally, sediment samples were collected from the intertidal zone on each profile and analyzed by dry sieving.

4. Results

Analysis of medium-term coastal changes reveals that the studied coast exhibits a great variety of shoreline evolution trends. A synthesis of coastal change rates recorded between 1956 and 2008 is presented in figures 2 and 3, where a different graphic representation of the results is shown for each proxy. The reason for this is the contrasting nature of the proxies: changes in the dune toe show a greater spatial variability and entail a lower degree of error, so they are represented on Cartesian axes to precisely show rates of change at detailed spatial scale; conversely, HWL trends are intrinsically more homogeneous and involve a higher uncertainty due to short-term phenomena (such as waves and tides), so they are represented on strips symbolized according to certain ranges of shoreline change.

In Figures 2 and 3 an overall pattern can be detected of prevailing erosion in the central-northern area and prevailing stability or even accretion in the southern zone. However, several important exceptions to this general trend can be found at certain points.

The Northernmost coastal sector, between Sanlucar and Rota (Fig. 1), is the one most severely affected by shoreline erosion, as this quite long coastal trait shows general retreat of both the dune foot and the HWL (Fig. 2 and 3). Shoreline recession between 1958 and 2008 is continuous and especially significant along the area between Aguadulce beach and Punta Candor, with a mean erosion rate of 0.7 m/yr that reaches up to 1.6 m/yr for both proxies at some points. Also the coast around Punta Montijo shows particularly severe recession, with an average retreat rate of 1.4 m/yr. On the other hand, significant beach accretion has been recorded in Regla beach, where HWL advance averages 0.8 m/yr (Fig. 3) and also the short-term beach profile monitoring showed an accretionary trend (Fig. 4-A).

APPROXIMATE POSITION OF FIGURE 2

APPROXIMATE POSITION OF FIGURE 3

In the Bay of Cadiz (Fig. 1) there are also some areas where significant beach erosion has been observed in the last decades. For instance, in Fuentebravia beach an average recession rate of 0.7 m/yr has been recorded in the HWL over the period 1956-2008 (Fig. 3), despite continuous nourishment works having been carried out since the 1990’s (Benavente et al., 2006a; Cooper et al., 2009). In some sectors an opposite trend is observed, like in La Puntilla beach, with a mean HWL advance rate of 4.2 m/yr that reaches 6 m/yr in its eastern sector (next to Guadalete river jetty), constituting the most rapidly accreting area along the whole study zone. This behaviour was also observed in the short-term evolution of the beach (Benavente et al., 2005b). However, the most remarkable beach regarding coastal changes is Levante beach, a unique erosional hotspot in Cadiz coast. At the southernmost end of Levante beach, dune retreat over the study period averages 6.2 m/yr, with some points reaching a recession rate above 10 m/yr for the dune foot and above 12 m/yr for the HWL (Fig. 2 and 3). Here nearly 66 Ha of beach, dune and salt marsh area have been lost in the last decades along a 1.5 km-long coastal trait. This extremely erosional trend was also observed in the short-term monitoring of a beach profile located in this area, where the base station placed in the foredune was lost several times.

APPROXIMATE POSITION OF FIGURE 4

The outer sector of the Bay of Cadiz includes both significantly eroding and predominantly accreting zones. Amongst the former it is worth mentioning Sancti Petri sandspit (Fig. 1), where Camposoto beach shows a mean retreat rate of both the HWL and the dune foot around 0.9 m/yr (Fig. 5) and a maximum of 1.4 m/yr at some points. Nevertheless, shoreline changes in this area are spatially irregular (Fig. 2), and general shoreline stability prevails in most of Cadiz city beaches, while significant beach and dune accretion has also been recorded at some specific points in this sector.

Further South, the area between the southern limit of Sancti Petri sandspit (Fig. 1) and Cape Roche shows a prevailingly erosive trend in its northern sector, while it is roughly stable in the southern sector. For instance, the northern sector of La Barrosa beach has been eroding at an average rate of 0.6 m/yr along the last decades (Fig. 3), although the most important retreat rates occurred between 1956 ands 1977, so short-term beach profile monitoring shows a relative stability (Fig. 4-B). South of this area, shoreline position is clearly stable both on a medium- and short-term basis.

APPROXIMATE POSITION OF FIGURE 5

Shoreline trends between Cape Roche and Cape Trafalgar (Fig. 1) are quite irregular, although rates of shoreline change are not as high as in other coastal sectors. This way, eroding areas such as southern El Palmar beach have recorded an average recession of the HWL between 0.4-0.5 m/yr. Conversely, dune advance rates about 0.6 m/yr have been recorded around northern El Palmar (Fig. 2), where the beach is relatively stable in the medium-term and slightly accretionary in the short-term (Fig. 4-C).

Stronger contrasts are found further South, between Cape Trafalgar and Punta Camarinal. Here the most severely eroding area is Caños de Meca, with an average beach and dune recession rate of 1 m/yr that reaches over 2 m/yr for the dune foot at some points (Fig. 2). Significant retreat of the HWL has also been recorded at other places such as the eastern part of Barbate sandspit, with erosion rates around 1.1 m/yr. However, the most important coastal changes in this sector have been recorded in La Hierbabuena beach and dunes, which show a continuous shoreline advance of 2.5 m/yr during the studied period (Fig. 2 and 3).

Finally, the southernmost sector of Cadiz coast can be considered relatively stable, except for some small areas where significant erosion or accretion has been recorded. This is the case in the western end of Valdevaqueros embayment, with a strong recession of the dune foot at rates close to 1.5 m/yr (Fig. 3). On the other hand, the northern sector of Los Lances beach has experienced around 0.5 m/yr of dune accretion, although the beach is quite stable both in the medium and short terms (Fig. 4-D). As for morphological and textural characterization of beach profiles, no clear geographic patterns have been recorded along the study area. Intertidal beach slope in the studied profiles ranges between 2.3% and 10.5%, although in most beaches it is lower than 6%. There is a certain tendency for intertidal beach slope to increase southwards, but several beaches differ from this general trend (Benavente et al., 2007). On the contrary, beach sediment size does not show any kind of pattern, as all the profiles are composed by medium sand, with D50 generally ranging between 0.28 and 0.40 mm. Sediment sorting is also very similar along the whole coast, with moderately classified sands that are slightly better sorted in the southern profiles.

5. Discussion

5.1. Spatial and temporal variability of shoreline trends

As previously stated, Cadiz coast exhibits a great spatial and temporal variety of shoreline evolution trends. In the areas where most important medium-term changes were recorded, there is a general coincidence between trends shown by the HWL and the dune foot (Fig. 2 and 3). This is the case at the most severely eroding zones, such as southern Levante beach, Punta Candor beach, Camposoto beach or Caños de Meca beach, and at the second most significantly accreting area, La Hierbabuena beach. Amongst these zones, in those where beach profiles were also monitored short-term beach changes show a general agreement with medium-term trends.

Nevertheless, there are several zones where both trends differ due to a variety of reasons, such as the greater uncertainty to which HWL changes are subject. This uncertainty is mainly related to the aforementioned short-term variability of this proxy, which is notably higher in the northern sector of the study area, due to higher tidal range and lower beach slopes. Besides, it is also important to note that both shoreline indicators represent different natural features with contrasting evolution mechanisms and response times (Boak and Turner, 2005). Dune erosion is usually quite fast and episodic, while dune accretion occurs more slowly over longer time periods. On the other hand, beaches are more dynamic and changeable, so the variability in beach erosion/accretion rates is much higher than that of dunes; moreover, beaches show lower thresholds for erosion (Del Río et al., 2012) and their response to changes in hydrodynamic conditions is much faster. This way, HWL advance in accreting beaches may not be reflected in a positive trend of the dune foot, or it may involve an important delay in the translation of beach changes into dune foot changes (Boak and Turner, 2005). In this sense, beach conditions along Cadiz coast show a great spatial variability regarding their suitability for dune formation, depending on variables such as coastal orientation, beach grain size, tidal range or backbeach characteristics (Gracia et al., 2006). Consequently, at some points the excess sediment on an accreting beach is not translated into dune formation but only into HWL advance, as occurs in La Puntilla beach (Fig. 3). The opposite situation can also occur, i.e. dune foot accretion not being associated to HWL advance, mainly due to human influence. This is the case in areas where dune accretion is promoted by preservation interventions such as dune fencing and grass planting, as occurred in northern El Palmar (Fig. 2), thus involving neither an increase in sediment supply nor beach advance.

On the other hand, beaches with berm and wide dry beach can experience HWL erosion without having dune stability affected, as the dunes would only be eroded by the most severe storms (Kraus and Rosati, 1997). In these zones opposite trends could be recorded for both shoreline proxies, with HWL recession and dune foot stability or even accretion, in case that it was a beach suitable for dune development; this occurs at some areas along Cadiz coast (Fig. 2 and 3). A different situation exists at Sancti Petri sandspit, which shows a general erosive trend as revealed by HWL retreat, short-term beach profile evolution and other geomorphological indicators (Benavente et al., 2002). Here the low occurrence of overwash events in the years before 2008, together with localized dune preservation interventions and beach replenishments has promoted the formation of new embryo dunes at the mouth of former washover areas, thus involving dune foot advance at some points.

Temporal distribution of shoreline changes also shows marked contrasts between different areas, related to the processes responsible for these changes. For instance, severely-eroding Punta Candor dunes have retreated at a nearly constant rate between 1956 and 2008 (Fig. 6A), probably due to the continuous action of erosion processes in this area, mainly related to nearshore bathymetry and coastal orientation. Conversely, extreme dune recession at southern Levante beach is mainly a consequence of specific human interventions at Guadalete river mouth (Martínez et al., 2001; Benavente et al., 2006b), thus showing important changes in erosion rates along the different periods studied (Fig. 6B).

APPROXIMATE POSITION OF FIGURE 6

5.2. Causes of shoreline changes

The spatial and temporal variability of shoreline changes in Cadiz coast can be related to both the above mentioned heterogeneity of the coast and the diversity of factors contributing to erosion-accretion processes in the area, with contrasting influence along the study zone.

Amongst the natural factors, the one that could be acting at a widest spatial scale is recent change in relative sea level. However, based on tide gauge data from the last decades, a very slightly rising relative sea level has been recorded in Cadiz harbour during the last century, i.e. 1.0 ± 0.2 mm/yr (Marcos et al., 2011), while relative sea level has remained stable in Tarifa harbour according to data supplied by the Permanent Service for Mean Sea Level (PSMSL, http://www.psmsl.org). Therefore, relative sea level rise is not to be considered a significant factor in determining recent shoreline evolution in Cadiz coast.

A very important natural factor causing shoreline erosion in the study area is the action of storms, which in Cadiz coast generally trigger beach flattening, erosive escarpments on beach and dunes and overwash processes (Benavente et al., 2002, 2006b), especially on steeper beaches due to their higher susceptibility to changes in wave regime (Cooper et al., 2004). Most of these effects are primarily found along beaches in the northern and central sectors of the study zone, where the energy of Atlantic storms is higher. Dune escarpments appear at places like Punta Candor, Levante, Camposoto or Caños de Meca beaches, while dune washovers are mostly located at Sancti Petri sandspit. Besides, outcrops of former saltmarsh sediments are frequently found after storms in the intertidal zone at Levante, Camposoto and Caños de Meca beaches.

The most intense storms over the last years occurred between December 1995 and February 1996, when a series of energetic, long-lasting storm groups coinciding with spring tides resulted in severe coastal damage along Cadiz coast (Benavente et al., 2006b; Del Río et al., 2012). Shoreline recession attributed to these events has been observed on the aerial photographs at certain areas, like northern Camposoto and northern Aguadulce beaches. Apart from these particularly energetic events, Rodríguez-Ramírez et al. (2003) identified a series of storm periods in the Gulf of Cadiz over the last decades, which undoubtedly have had a great influence on recent shoreline evolution in the study area. Unfortunately, the low temporal resolution of the aerial photographs used in the present work prevents a specific identification of the effects of each storm period. It must be noted that the intensity of damages caused by a certain storm depends on its relative magnitude (Cooper et al., 2004), for instance on the relationship between storm wave height and modal wave height in the study area. In this respect, on the low-energy coast of Cadiz the occurrence of high-energy events like those of 1995-1996 produces serious damage and the need for a long recovery period for beaches to return to equilibrium with prevailing hydrodynamic conditions (Benavente et al., 2000). Moreover, dune recovery after these events may not take place for a long time, since eroded dune systems require greater amounts of sediment and longer time periods to build up new dunes and recover the eroded dune front (Lentz and Hapke, 2011).

Besides storminess, the main natural factor determining shoreline evolution in the study area is constituted by coastal setting, including both nearshore bathymetry and coastal orientation. In Cadiz littoral, the former plays an especially significant role where rocky shore platforms modify diffraction/refraction wave patterns and can generate erosional hotspots (Kraus and Galgano, 2001; Anfuso et al., 2008). This occurs at areas like Punta Candor, Camposoto or Caños de Meca (Fig. 2 and 3). Also seafloor bathymetry on areas located at some distance from the coast can influence erosion-accretion processes. In the study area, submarine reliefs offshore Cape Trafalgar (Fig. 1) partially block longshore drift, so sediment accumulates on the inner shelf (“Placer de Meca” sand deposit) and causes sediment deficit in Caños de Meca. Moreover, not only rocky features, but also sandy shoals influence coastal erosion, as occurs at Sancti Petri tidal inlet; here longshore sediment transport and complex tidal currents give rise to a sandy shoal that significantly contributes to sediment deficit at Sancti Petri and northern La Barrosa beaches (Del Río et al., 2008). Regarding coastal orientation, it contributes to erosion in specific areas by increasing exposure to energetic waves, as occurs in Punta Candor or the western portion of Valdevaqueros embayment.

In fact, the absence of clear spatial patterns in short-term beach changes along Cadiz coast can be mostly attributed to either local control factors regarding geological framework (Jackson et al., 2005; Lentz and Hapke, 2011), as occurs close to rocky platforms and headlands, or hydrodynamic conditions (Benavente et al., 2007), as occurs close to tidal inlets and river mouths. For instance, no clear trends are observed in the evolution of the headland-bay systems located at the southern end of the study area, which are mainly controlled by local features related to their z-bay planform and to the strong influence of aeolian dynamics close to the Strait of Gibraltar.

Apart from these natural factors, there are several human-related causes that influence shoreline trends in Cadiz coast. The most important one is the building of dams on Guadalquivir, Guadalete and Barbate river basins (Fig. 1), as fluvial sediments get trapped in the reservoirs causing sediment deficit in the coastal zone and subsequent shoreline erosion (Komar, 2000). Most dams in this region were built during the 1960s and 1970s, and as a consequence nearly all beaches in the study area recorded HWL and dune erosion in the period between the two first photogrammetric flights (1956-1977). The most affected areas are the northern and central coasts of the province, mainly between the Bay of Cadiz and Punta Camarinal, where in many beaches the greatest shoreline retreat was recorded in that period. Beaches in the southernmost coastal areas are less influenced by Guadalquivir, Guadalete and Barbate rivers because of the distance from them, the already mentioned particular wind and wave regime near the Strait of Gibraltar, and the lower intensity and sediment load of longshore drift southward of Cape Trafalgar, Punta Camarinal and Punta Paloma headlands (Fig. 1). Other significant human-related factor causing particular erosion-accretion patterns at certain points in the study area is the building of coastal engineering structures. The most relevant example is the case of Levante beach at Valdelagrana spit-barrier, where the diverse phases of jetty construction and lengthening at Guadalete river mouth are responsible for remarkable shoreline accretion at the northernmost end of the beach and extreme coastal retreat episodes at the southern end of the spit, due to the disruption of the log-spiral equilibrium beach planform (Martínez et al., 2001; Benavente et al., 2006b). Immediately to the North, the artificial enclosing of La Puntilla beach between Guadalete river jetty and a nearby recreational harbour has led to massive sand accumulation and shoreline advance (Fig. 7). Also the groins of NATO Base at Rota have caused serious downdrift sediment deficit at Fuentebravia beach, leading to the need for shoreline armouring and periodic artificial nourishments (Benavente et al., 2006a; Cooper et al., 2009) and contrasting with updrift beach accretion. Shore-parallel structures, which are widespread along urban areas in Cadiz coast, have a strong influence in local cross-shore sediment balance, as seawalls or rip-rap revetments can increase coastal erosion by wave reflection and by preventing profile adaptation to wave conditions (Trenhaile, 1997); this occurs at places like the northern portion of La Barrosa beach. These structures can also intensify erosion on adjacent areas, as observed next to rip-rap-protected houses in the coastal sector between Aguadulce and Punta Candor.

APPROXIMATE POSITION OF FIGURE 7

In this sense, general backbeach artificialisation, especially important in the northern and central parts of the study zone, caused massive dune destruction prior to 1980's. In these areas beach sedimentary buffer was eliminated and cross-shore sediment budget became negative, increasing coastal vulnerability to erosion; this was the case in places such as northern La Barrosa beach and Caños de Meca.

Finally, the role of artificial beach replenishments in shoreline changes must be mentioned, as these projects have been performed extensively in the study area (Muñoz-Pérez et al., 2001; Benavente et al., 2006a). In the short term, artificial beach nourishments may mask naturally erosive trends revealed by medium-term photo analysis, as occurs in Cadiz city beaches and northern La Barrosa. In certain cases, this type of interventions can contribute to prolonged overall stability not only in the replenished zone but also in downdrift areas (Lentz and Hapke, 2011), as recorded southwards of Cadiz city urban beach.

5.3. Factors determining beach behaviour

From the above considerations it appears that aspects related to coastal geological setting (such as beach planform or nearshore morphology) are the main reason behind the contrasting shoreline trends observed along Cadiz beaches. In this regard, it is clear that factors and processes involved in beach erosion depend on coastal morphological and dynamic characteristics. For this reason, beaches in the study area have been classified into four groups according to these features, so that erosion mechanisms occur in a particular way on each group. It must be noted that this classification is neither homogeneous nor exclusive, so several beaches can be assigned to more than one group. The first group is constituted by *rectilinear, long and regular beaches*, mainly structurally controlled, that appear on a great part of the northern study area and at some points in the South, being 17 out of the 58 analysed beaches. Here waves usually reach the coast with a certain approaching angle, giving rise to significant longshore transport and minor cross-shore transport; therefore, these are mostly drift-aligned beaches according to Davies (1980). Beach profile morphology is generally intermediate to dissipative according to the general terms by Wright and Short (1984). They tend to develop in areas directly affected by river sediment supply (Komar, 1998; Woodroffe, 2002), such as the northern portion of the province (Guadalquivir and Guadalete rivers), Zahara beach (Barbate river) (Fig. 8A) and, to a lesser extent, El Palmar beach (Salado stream) and Los Lances beach (Jara and Vega streams). On areas with significant longshore drift, rectilinear beaches generally behave as sediment by-pass zones, hence showing certain stability without sediment losses or gains; this occurs in areas such as the sector immediately south of Cadiz city. However, nearshore bathymetry at certain rectilinear beaches can focus wave energy and produce localized erosion, as occurs in central Sancti Petri sandspit due to the wide gap existing in an offshore, discontinuous rocky shoal located at 5 m depth below LLWS (Benavente et al., 2002). In fact, an irregular alternance of erosive, accumulative and stable coastal trends can be found in this area (Fig. 2), due to a combination of factors including the aforementioned gap in the rocky shoal, overall reduction in sediment supply, artificial nourishment works, alternate periods of washover reactivation and dune weakening by human transit.

The second group is constituted by *reef-supported beaches*, which includes 22 beaches, such as those in the Chipiona-Rota sector (Fig. 8B). Profile morphology in this type of beaches is relatively steep, with the monitored profiles being truncated by intertidal or subtidal rocky shore platforms. In fact, these beaches are usually characterized by a reduced sand volume, limited by the rocky substrate, and they generally evolve by parallel retreat due to the difficulties in cross-shore sediment exchange (Muñoz-Pérez et al., 1999). Beach sediment eroded by storms can reach areas further offshore than the edge of the shore platform, so the rocky shoal often constitutes an obstacle for sediment return under fair weather conditions (Kraus and Galgano, 2001). Sediment deficit usually renders these beaches erosive in the medium-term, as recorded in most of the Chipiona-Rota sector or in Caños de Meca beach. However, at the same time rocky shore platforms dissipate wave energy, thus contributing to beach protection, as occurs in the area located north of Sancti Petri sandspit. Besides, at certain areas rocky shore platforms act as groins by blocking longshore transport, so that updrift beaches experience accretion (Benavente et al., 2000; Anfuso et al., 2008), while downdrift beaches record erosion, like the northern sector of Sancti Petri sandspit. On the other hand, gaps in the rocky shore platforms can induce wave energy concentration and increased erosion; in fact, some of the most severely eroding beaches in the study area are those laterally limited but not fronted by submerged rocky shore platforms, such as Caños de Meca beach or the area located just north of Punta Candor.

APPROXIMATE POSITION OF FIGURE 8

The third group is that of *z-bays* or *crenulate-shaped beaches* (Yasso, 1965), developed downdrift of a headland and thus more frequent in the southern part of the province due to the presence of coastal reliefs and headlands. Beach planform is asymmetrical, with a curved coastline in the shadow zone immediately downdrift of the headland, a central sector with a minor curvature, and a rectilinear distal sector that is roughly parallel to prevailing wave fronts (Woodroffe, 2002). In the study area the latter can extend up to several kilometers, so at certain embayments such as Sancti Petri sandspit the northern zone could be considered as a z-bay beach whereas the southern area is clearly rectilinear. Because of the varying influence of the headland, z-bays usually show a gradation in beach slope and grain size, so on sandy beaches the shadow zone typically presents steeper slopes and coarser sediments than the exposed area (Yasso, 1965; Terpstra and Chrzastowski, 1992; Woodroffe, 2002); this occurs at nearly all the 5 crenulate-shaped beaches identified on Cadiz coast, such as Levante and Valdevaqueros (Fig. 8C).

No clear patterns have been recorded concerning medium-term sediment transfer within z-bays. Erosion at the distal zone and stability or accretion at the shadow zone occur at Levante and El Carmen beaches. As mentioned in section 5.2, the recent evolution of Levante beach is determined by the building and lengthening of jetties on Guadalete river mouth, which have shifted the upcoast control point of the log-spiral (i.e. the point from which wave diffraction starts) southwestwards. As a consequence, the planform shape of the spit barrier has been rotating to reach an equilibrium morphology adapted to the new conditions, by eroding in the southern end and accreting in the northern (Martínez et al., 2001). Nowadays the beach planform seems to be reaching a new dynamic equilibrium (Fig. 6B). El Carmen beach, located on Barbate sandspit, is limited to the West by a fishing harbour and to the East by Barbate river mouth (Fig. 9). Here medium-term shoreline evolution takes place by beach rotation or pivoting (Short and Masselink, 2001) around its central zone, with accretion at the western zone and erosion at the distal end of the spit (Fig. 9). This pattern is probably related to sediment deficit due to massive retention in La Hierbabuena beach (located updrift from the harbour); the distal area of the spit would not be much affected, as it receives a certain sediment supply from the river and waves under easterly wind conditions.

APPROXIMATE POSITION OF FIGURE 9

As opposed to the aforementioned pattern, shadow zone erosion and distal zone stability have been observed at other z-bay systems in Cadiz coast. In this sense, the most open z-bays (such as La Barrosa) should in fact be considered as rectilinear beaches with a certain downdrift erosion at the shadow area of the headland, but without the characteristic curvature of crenulate-shaped beaches, mainly due to the small size of the headland on each case. Valdevaqueros is a special case of z-bay, generated by Poniente swell waves (see section 2) but, due to the proximity of the Strait of Gibraltar, strongly affected by Levante sea waves, which produce the above mentioned erosion at the westernmost zone of the embayment.

The last group corresponds to the *beaches enclosed between two structures*, relatively small and showing a regular shoreline (i.e. not asymmetrical as in z-bays). In Cadiz coast most of the 14 beaches that have been ascribed to this group are enclosed between a natural headland and an artificial structure (a groin or jetty), as occurs in Regla, La Puntilla or La Hierbabuena beaches, most of them also backed by a seawall and without dunes. Only some small pocket beaches, such as those around Cape Roche or El Cañuelo beach (Fig. 8D), are fully limited by cliffed headlands and can thus be considered as having a completely natural origin. According to classical models, enclosed beaches can either be swash-aligned (pocket beaches) or drift-aligned (Davies, 1980), but in the study area most enclosed beaches have intermediate morphologies between both types.

Regarding evolution trends of enclosed beaches, they are determined by the source and magnitude of sediment supply. This way, shoreline changes are minimum at places where no significant interventions on sediment transport have occurred, as the equilibrium between sediment supply and redistribution by waves was reached long ago, so the beach is virtually stable (Komar, 1998). Conversely, where longshore drift has been interrupted by artificial structures shoreline changes have occurred very rapidly, as in La Puntilla (Fig. 7) or La Hierbabuena (Fig. 10) beaches (Gracia et al., 2006).

APPROXIMATE POSITION OF FIGURE 10

A comparison between all these beach types and medium-term shoreline evolution trends is presented in figure 11 for both the HWL and the dune toe. It must be noted that the figure represents average data for each individual beach (mean rate of shoreline change and standard deviation for each group), so that opposite trends at different zones of a single beach result in an overall stable trend for that beach. This is the reason why stability appears to be the prevailing trend in the study area, which is not exactly true especially in z-bays, where most of them experience erosion at one end and accretion at the opposite end.

As observed in figure 11, a very good agreement exists between both shoreline proxies. This means that, in general, HWL and dune toe trends show the same behaviour when average rates of shoreline change for groups of similar beaches are used. From a methodological perspective, this is particularly important considering that the HWL is often dismissed as shoreline indicator in tidal environments like Cadiz coast. These results would thus support the reliability of the HWL as a shoreline proxy when dealing with average data.

Regarding beach behaviour, on a broad sense it can be noted that rectilinear beaches are predominantly stable or accreting (Fig. 11), and dune foot advance is more likely to occur here than in most other types of beaches, partly because their morphology in the study area is generally more suitable for dune development. Dune restoration projects carried out at some rectilinear beaches also contribute to the recorded accretionary trends.

Reef-supported beaches are the most erosive type (Fig. 11) as a consequence of their morphodynamic characteristics, mainly the sediment deficit when compared to other types of beaches. This kind of beaches is protected by rocky shore platforms against energetic waves associated with modal storms, but return of eroded sand to the beach during fair weather conditions is prevented by the rocky barrier. As a consequence, low frequency, high energy events produce severe erosion which is not balanced during calm periods. Hence, reef-supported beaches record a slow but maintained sediment deficit in the medium term.

As previously discussed, z-bays generally experience erosion at one end and accretion at the opposite end, being very sensitive to changes in the diffraction control point. Due to their dynamic complexity, changes in sediment supply or in wave climate produce rapid morphological adjustments. Intermediate planforms between pure crenulate-shaped beaches and rectilinear beaches are quite common, especially when considering long z-bays with an extended downdrift sector. This is the reason why rectilinear and z-bay beaches show a fairly similar behaviour in the medium term (Fig. 11). The more limited range of change in the latter may be due to their semi-confined nature, al least at their updrift end, which partly protects the beach against energetic waves, but at the same time hinders longshore sediment inputs.

Finally, enclosed beaches tend to be predominantly stable or accreting due to their *cul-de-sac* morphology, but they show the highest variability in rates of shoreline change (Fig. 11) because of their strong dependency on local control factors, mainly regarding sediment supply.

APPROXIMATE POSITION OF FIGURE 13

6. Conclusions

In this work the recent evolution of sandy shores along the 150 km long Atlantic coast of Cadiz province (SW Spain) has been obtained by means of aerial photographs and topographic monitoring of beach profiles. It has been found that shoreline changes over the last 50 years show a great spatial and temporal variability. Strong differences in evolutive trends found between the northern-central sector of the study area and the southern one (closer to the Strait of Gibraltar) are due to a variety of reasons. These include a higher dependence of northern beaches on river sediment supply, general stability of enclosed beaches (which are more often found in the southern sector due to coastal topography) and higher levels of human interventions in the northern-central sector, including coastal engineering structures and backbeach occupation. However, other factors related to local hydrodynamic and geologic constraints also have a major influence on shoreline changes at some points.

From the results obtained, a morphological and evolutionary classification of sandy beaches has been proposed on the basis of beach planform, according to the way shoreline morphology influences erosion-accretion trends. The classification, which can be applied to sandy shores in other areas of the world, allows identifying those beaches which are most sensitive to variations in controlling factors. This way, rectilinear beaches tend to show predominantly stable or accreting behaviour, and they are strongly dependent on changes in sediment supply. On the contrary, negative sediment budget is common in reef-supported beaches, which generally exhibit erosional trends related to the barrier effect of the rocky shore platforms. Z-bay beaches are extremely sensitive to variations in headland configuration, and they usually show contrasting shoreline behaviour at both ends, while the evolution of enclosed beaches, which generally show accretionary behaviour, is greatly determined by human interventions on sediment budget.

From a methodological point of view, GIS-assisted, detailed analysis of the high-water line and dune toe positions on aerial photographs constitutes an extremely useful tool for studying medium-term coastal evolution, showing in most cases a general agreement with the results of short-term topographic surveys. However, in cases where evolution patterns are more complex the limited scale of beach monitoring renders it difficult to obtain conclusive data. Future research could be focused on these areas, by making use of hydrodynamic modelling and in situ measurements to investigate wave propagation and sediment transport processes on a local basis. Nevertheless, the strong influence of the above cited factors of local control would very probably require simplifying or ignoring some of these features, for example when applying wave propagation models on nearshore areas of reef-supported beaches. Therefore, the only use of this type of approaches would not be entirely satisfactory, but would support the detailed analysis of aerial photographs as an essential means for understanding general evolution and dynamics of coastal areas. Further research could also include the use of equilibrium planform models and hydrodynamic records from the last decades, in order to evaluate the relationships between patterns of wave energy (e.g. storminess) and recent changes in beach planform on each beach type.

From an applied point of view, the results obtained are not only useful in forecasting general shoreline behaviour in the near future, but also in selecting the most adequate type of intervention when managing retreating coasts. For instance, results indicate the difficulty of preventing erosion in reef-supported beaches, while dune restoration seems to be an efficient measure in rectilinear eroding beaches. Therefore, this type of studies constitute basic tools of general interest in coastal land use planning and coastal management, as they help identifying the causes and hence the most adequate solutions and interventions for addressing problems related to undesired shoreline changes. In this way they can contribute to decreasing the impacts and risks associated with coastal zone dynamics, especially important in the context of increasing coastal population and future climate change scenarios.

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Figure captions

Figure 1. Location map of the study area.

Figure 2. Rates of dune foot change recorded between 1956 and 2008 in the study area. Labels indicate the main beaches and landmarks mentioned in the text. Dots indicate the population centres shown in Fig. 1.

Figure 3. Main trends in HWL change recorded between 1956 and 2008 in the study area. Labels indicate the main beaches and landmarks mentioned in the text. Dots indicate the population centres shown in Fig. 1.

Figure 4. Examples of topographic beach profiles monitored along the study area (dashed lines mark the mean sea level, MHWS and MLWS). Secondary plots on each profile show the evolution of the distance between the profile base station and the mean high water level, in the winter surveys (dashed line is the linear regression fit).

Figure 5. Changes in dune foot position between 1956 and 2008 in Camposoto beach. Background image is 2008 orthophotograph.

Figure 6. Examples of contrasting temporal distribution of dune foot recession. The arrows in the photographs point at transects represented in the graphs below. Background images are 2008 orthophotographs. A) Constant erosion rates at Punta Candor. B) Extremely changing erosion rates at Punta de los Saboneses (southern Levante beach).

Figure 7. Extreme advance of HWL position between 1956 and 2008 in La Puntilla beach. Background image is 2008 orthophotograph.

Figure 8. Oblique aerial photographs showing examples of beach types (A, B and D photographs courtesy of the Spanish Ministry of Environment). A: Zahara beach, rectilinear. B: Southern Aguadulce beach, reef-supported. C: Valdevaqueros beach, z-bay. D: El Cañuelo beach, enclosed.

Figure 9. Shoreline changes in El Carmen beach between 1956 and 2008. Background image is 2008 orthophotograph.

Figure 10. Shoreline accretion at La Hierbabuena beach and dunes between 1956 and 2008. The arrows are indicating the same points in both photographs.

Figure 11. Distribution of mean values and standard deviations of shoreline trends amongst the different beach types along Cadiz coast, according to the obtained rates of dune foot and HWL change. The trends have been extracted from average data of each individual beach, so that opposite trends at different zones of the same beach result in an overall stable trend for that beach.

Table captions

Table 1. Aerial photographs and orthophotographs used in this study.

Table 1.

Flight date	**Executed by**	**Scale**	**Type**
Nov 1956 - Jan 1957	U.S. Army	1:33,000	B/W
1977	IRYDA – Ministry of Agriculture	1:18,000	B/W
Sep 1982	National Geographic Institute (IGN)	1:30,000	B/W
Jul 1984	CECAF – Spanish Air Force	1:30,000	B/W
Aug 1985	CECAF – Spanish Air Force	1:18,000	B/W
Apr - Jun 1986	CECAF – Spanish Air Force	1:18,000	B/W
Aug - Oct 1992	Andalusian Cartography Institute (ICA)	1:20,000	B/W
Jul 1994	Andalusian Cartography Institute (ICA)	1:15,000	B/W
Jul - Sep 2002	Andalusian Cartography Institute (ICA)	0.5 m resolution	ortophoto B/W
Aug - Nov 2008	Andalusian Cartography Institute (ICA)	0.5 m resolution	orthophoto RGB

Figure 1 revised

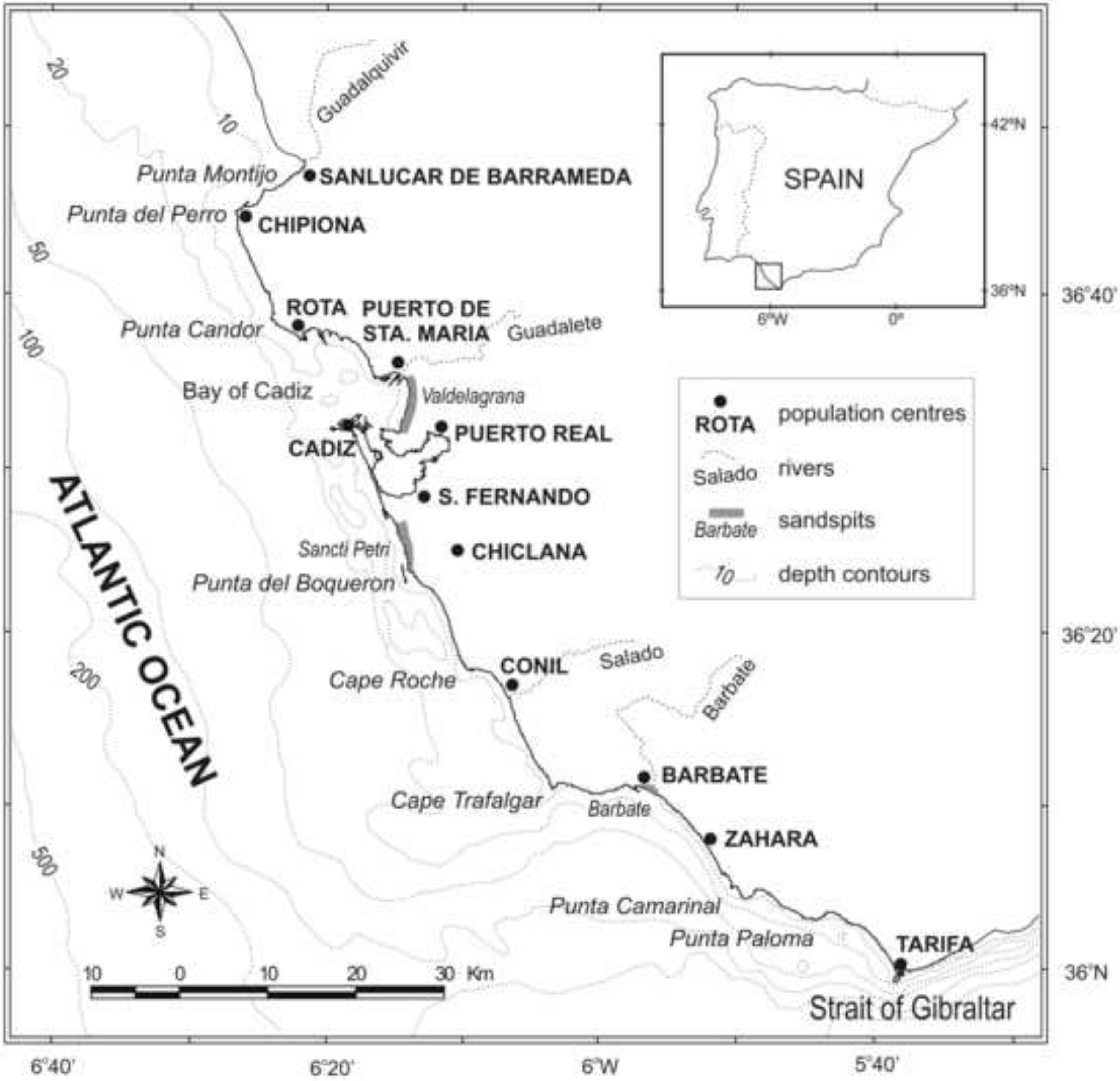

Figure 2 revised in EPS format

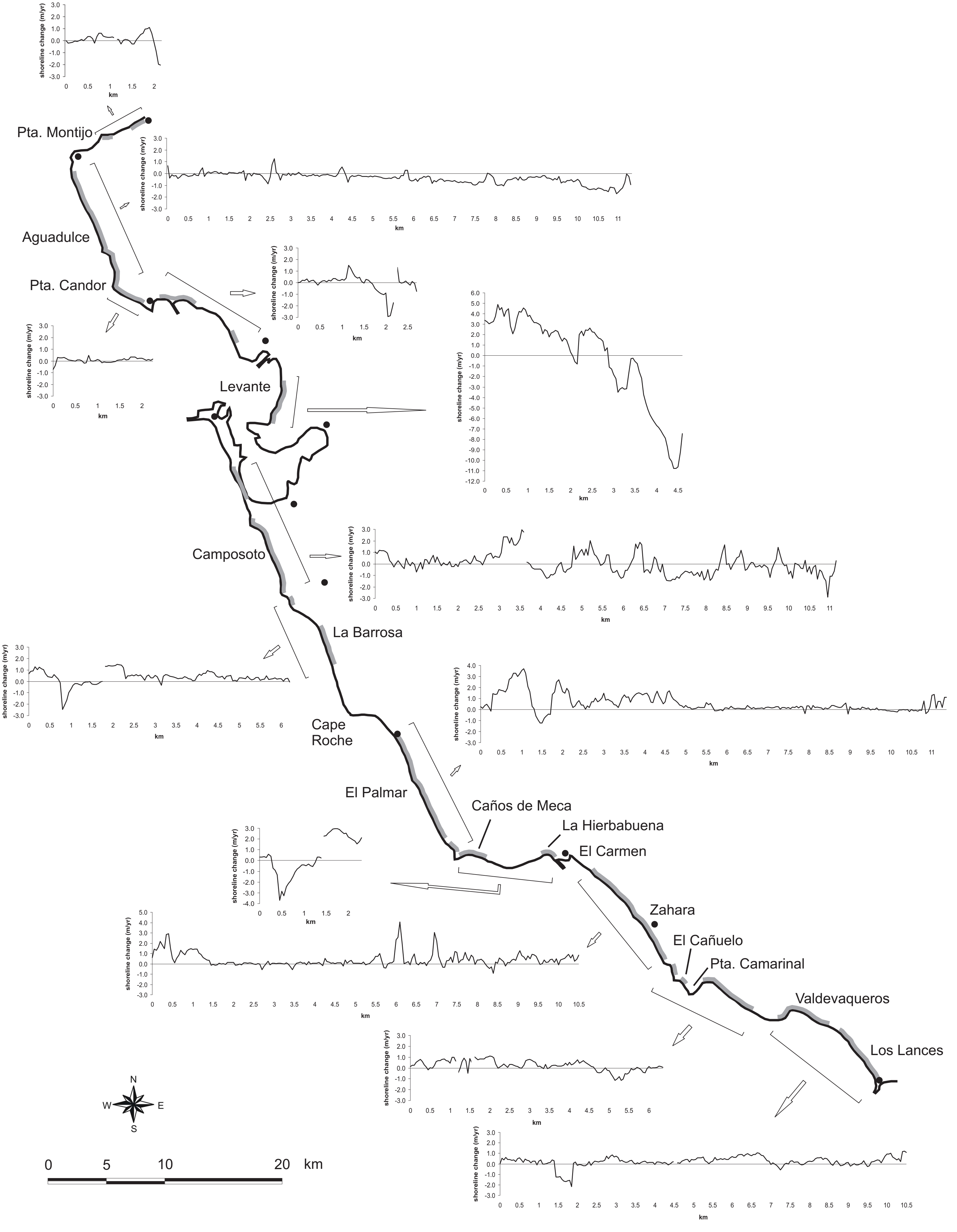

Figure 3 revised (colour) in EPS format

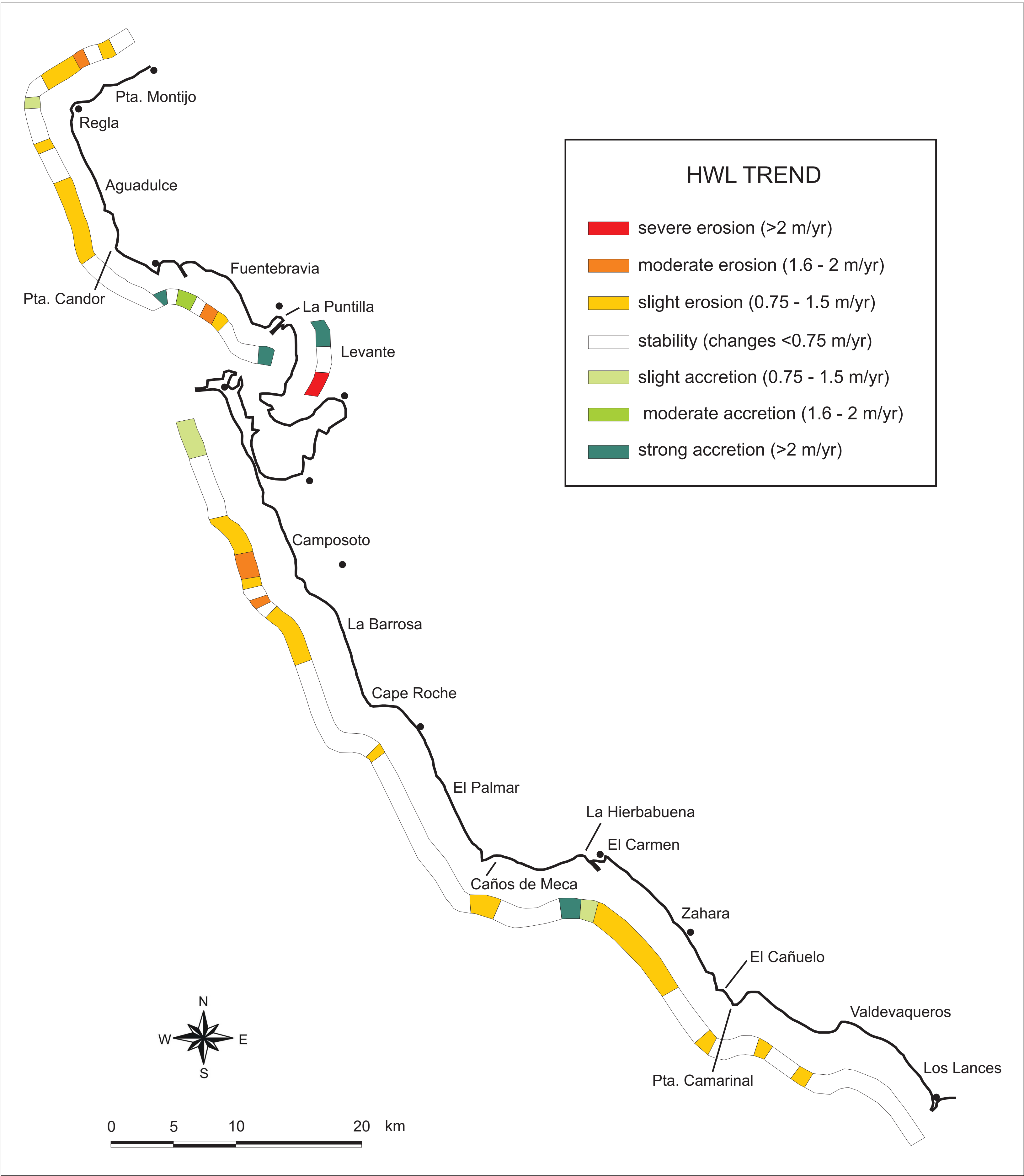

Figure 4

Click here to download high resolution image

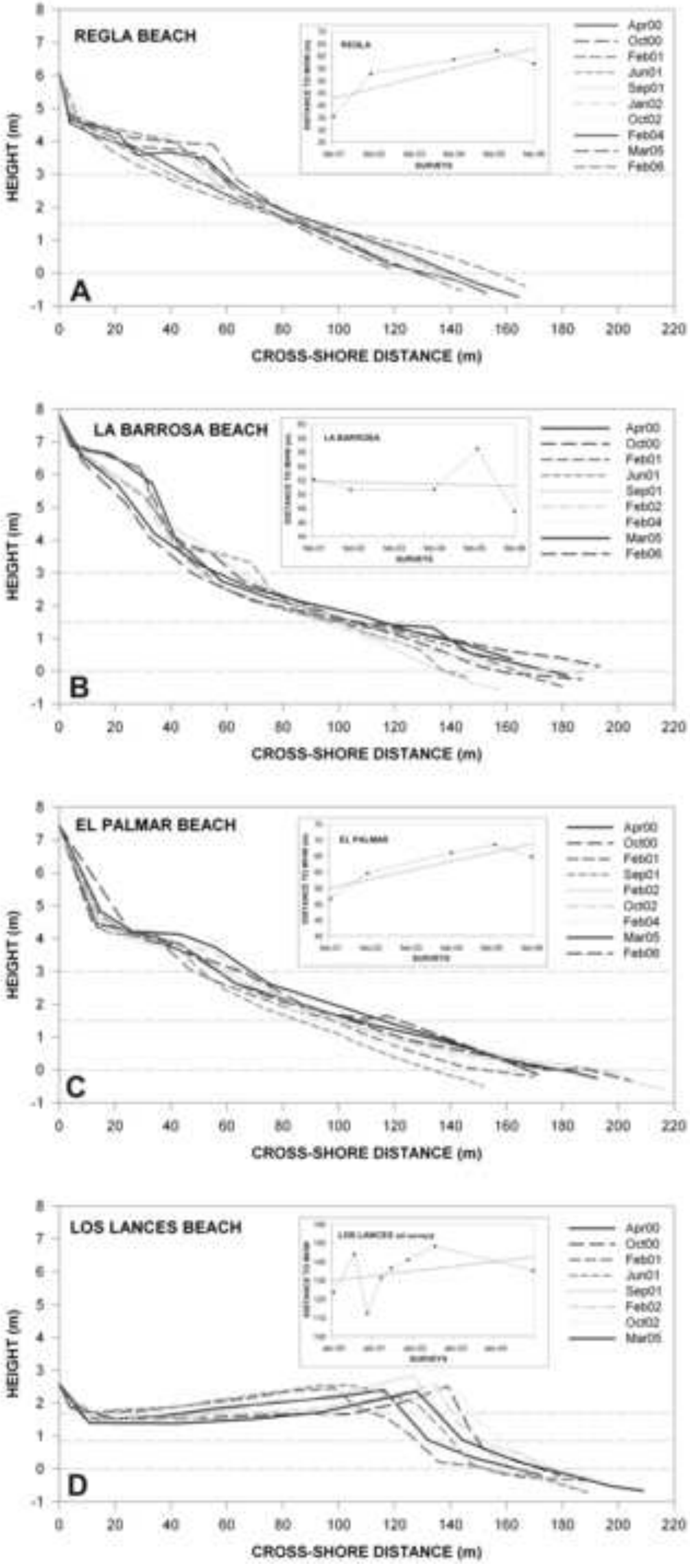

Figure 5 (colour)

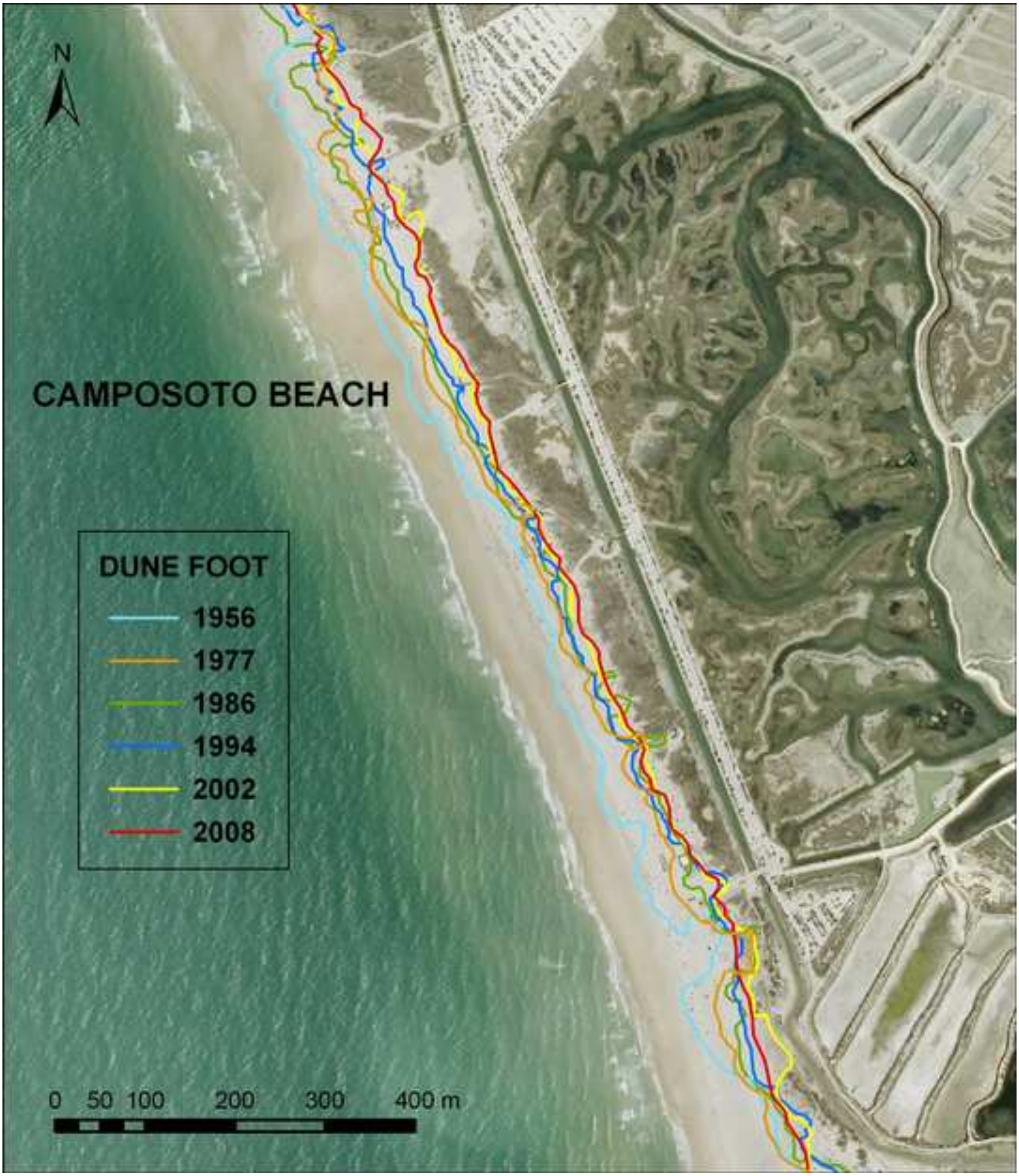

Figure 6 revised (colour)

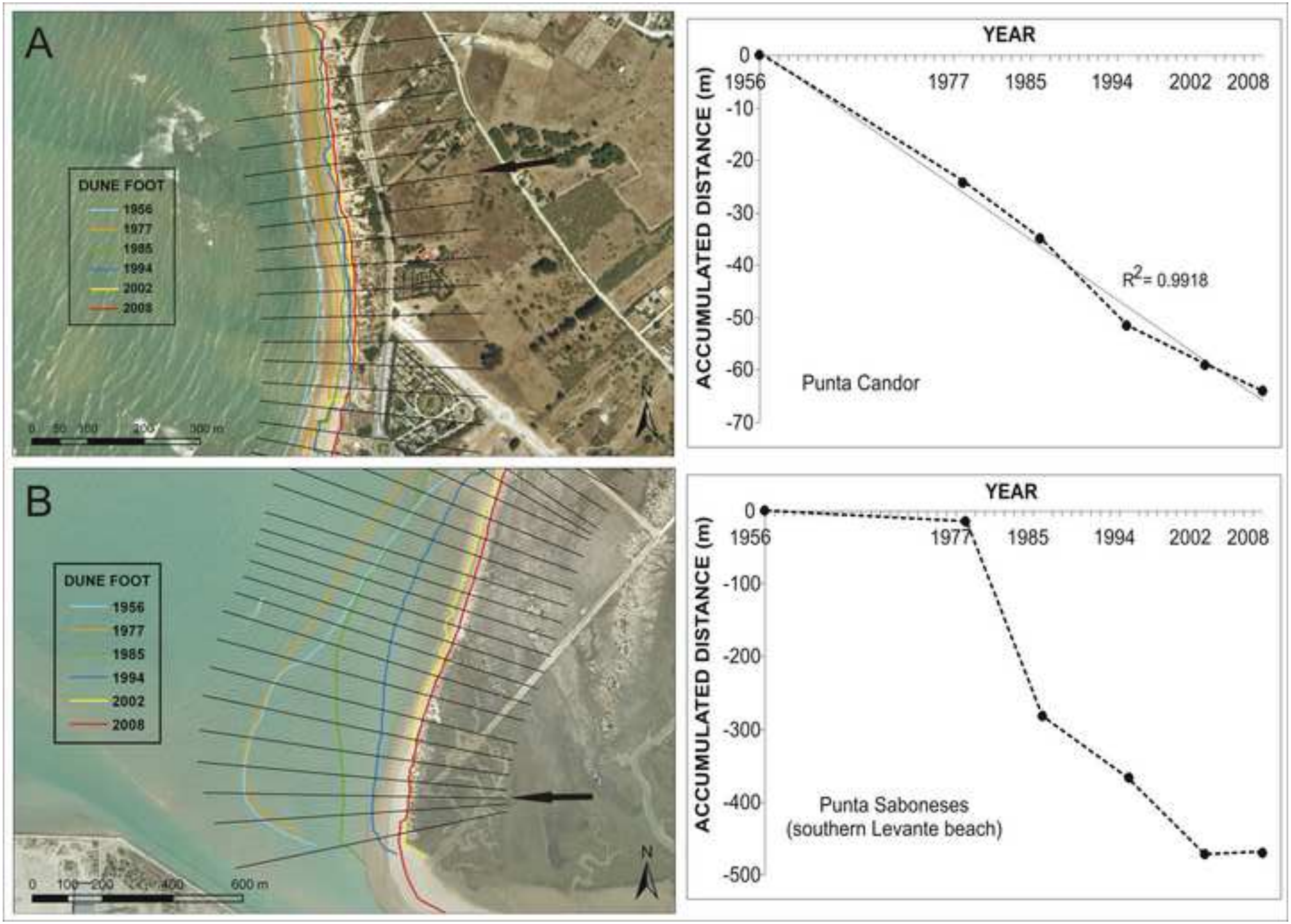

Figure 7 (colour)

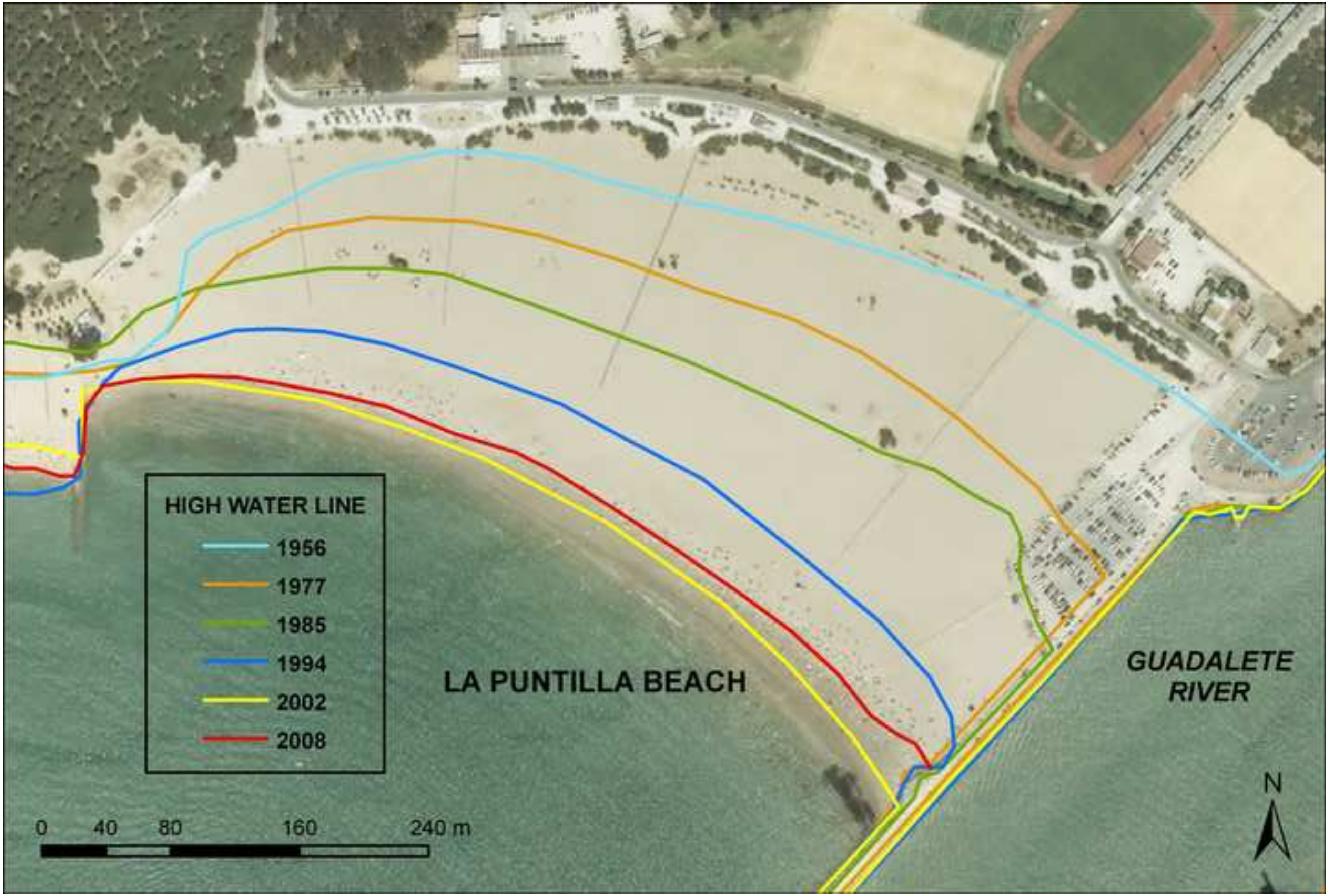

Figure 8 revised (colour)

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Figure 9 (colour) renumbered

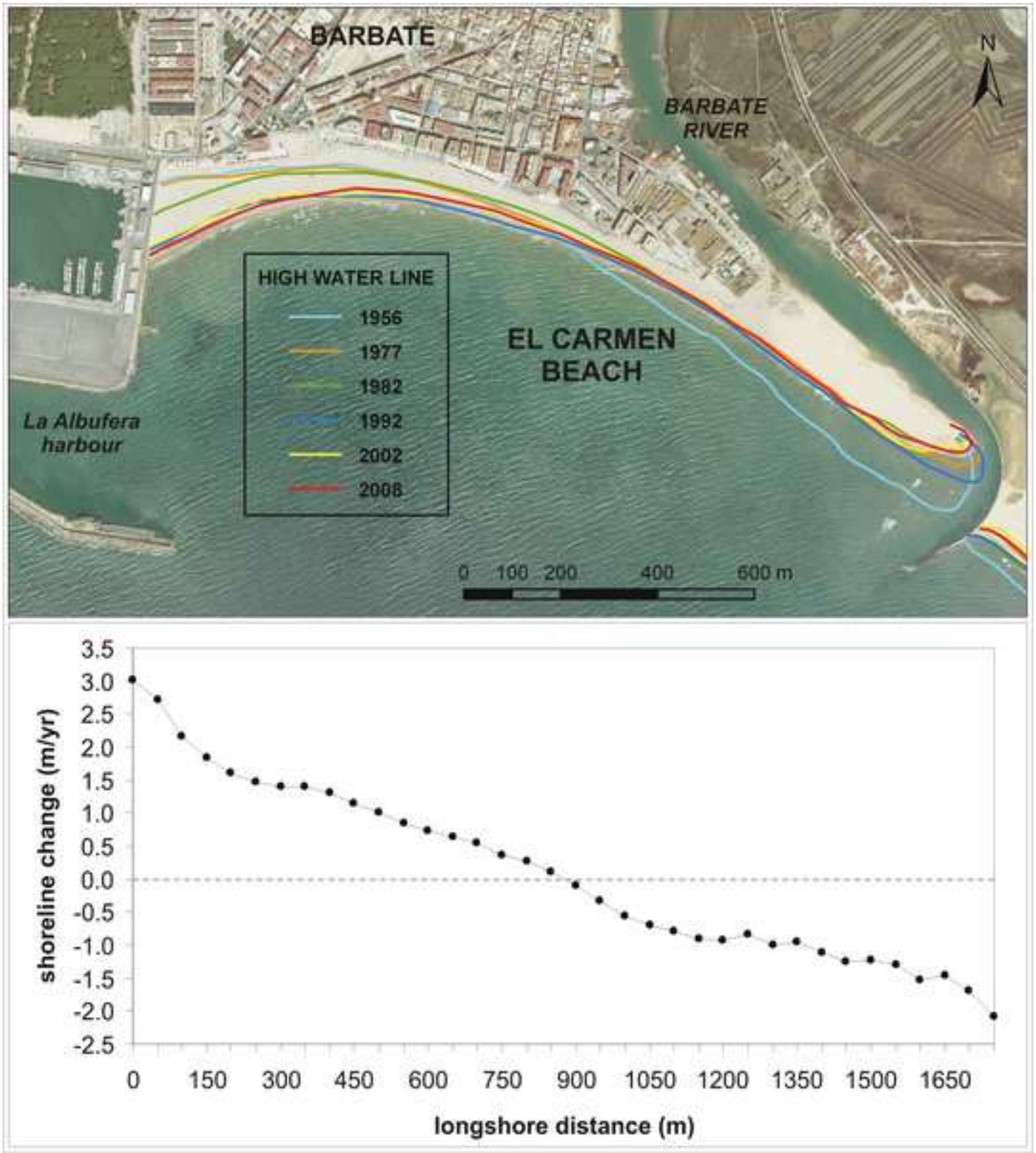

Figure 10 renumbered

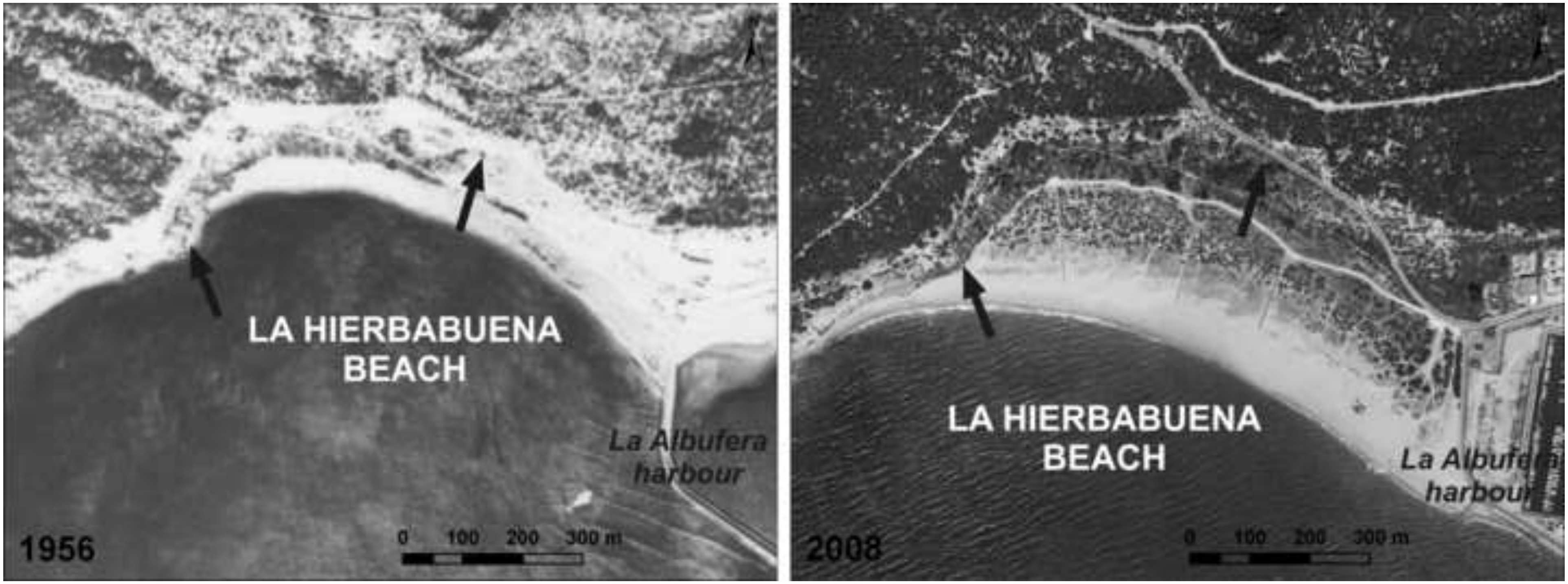

Figure 11 revised