Chapter 8
Anthropogenic Influence on Spit Dynamics at Various Timescales: Case Study in the Bay of Cadiz (Spain)

L. Del Río, J. Benavente, F.J. Gracia, C. Alonso, and S. Rodríguez-Polo

Abstract Human interventions are one of the main drivers of coastal change in many areas, often generating undesired impacts like shoreline retreat. Sandspits are especially sensitive to anthropogenically-induced changes, especially those related to sediment supply. This work presents a case study of Valdelagrana spit in SW Spain, a sandbody where anthropogenic influence has been evident since Roman times. A variety of methods were applied to assess geomorphological and morphodynamic changes in the area at various timescales. Historical interventions involve mainly river course diversion, which caused important changes in sediment supply. More recently, coastal engineering structures and land reclamation deeply modified wave and current patterns in the area, triggering massive coastal erosion. As a consequence of this, the system has evolved from a drift-aligned spit to a swash-aligned barrier. This study provides insights into the consequences of human interventions at similar coastal settings.

8.1 Introduction

The dynamic nature of coastal systems is related to a variety of drivers, of both natural and anthropogenic origin, often acting simultaneously at different spatial and temporal scales. In this respect, it has been widely stated that anthropogenic influence on coastal behaviour has greatly increased worldwide over recent decades due to the accelerated occupation of littoral zones which had remained pristine until recent times (Komar 2000). However, in some areas where development started in ancient times, anthropogenic transformations of coastal landscape and dynamics have been going on for centuries.

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G. Randazzo et al. (eds.), *Sand and Gravel Spits*, Coastal Research Library 12,
DOI 10.1007/978-3-319-13716-2_8

This human influence on coastal behaviour generally involves changes in the conditions that determine the geomorphological and morphodynamic character of each particular coastal area. The most common small-scale impacts are related to interventions altering local sediment budget on the coast, such as building shoreline defence structures, sand mining, artificial beach nourishment or destruction of coastal natural systems by urban development, among others (Komar 2000). The main medium- and large-scale impacts are associated with human interventions on river basins, such as dam construction (Syvitski et al. 2005), and those related to sea level rise and coastal erosion (FitzGerald et al. 2008).

The extent and nature of the effects of these activities will depend on the type of coastal system involved. Sandy coasts are extremely dependant on sediment supply, so their evolution and behaviour will be highly determined by human interventions that alter the sediment budget. In this regard, sandspits are particularly sensitive to changes in conditions such as wave approach direction or sediment input (Komar 1998).

This work presents a case study of Valdelagrana spit barrier in SW Spain, a sandbody where different types of human interventions at various timescales have been altering the natural behaviour of the system during the past 2,000 years. The analysis of this study case provides an understanding the response of a sandspit to anthropogenic modifications at diverse spatial and temporal scales. Thus, it can ultimately contribute to predict future consequences of planned interventions at similar settings, in order to avoid undesired impacts.

8.2 Study Area

Valdelagrana spit barrier is located in the Bay of Cádiz (SW Spain) (Fig. 8.1). It is a north-south oriented sandy body with a total length of 7.2 km and an average width of 1.5 km, running from the Guadalete River mouth to the outlet of Río San Pedro tidal channel. Guadalete River is the main fluvial course in Cádiz province with a total length of 170 km and a drainage basin of 3,677 km^2. The river mouth at the northern limit of the study area is a 200 m wide, tide-dominated estuary.

Valdelagrana shoreline shows a Zeta-bay shape developing downdrift of Santa Catalina headland (Martínez del Pozo et al. 2002), but due to wave refraction around Cádiz tombolo it is a mixed geomorphic system between a drift-aligned spit and a swash-aligned barrier (Benavente et al. 2006). It includes a broad range of morphosedimentary environments, both active and relict (Fig. 8.1): a sandy beach (Valdelagrana or Levante beach); embryo dunes and discontinuous ridges of foredunes less than 2 m high; four Holocene beach ridges indicating old growth stages of the spit (Zazo et al. 1994); mud flats; and wide areas of vegetated salt marshes. The area is crossed by two narrow tidal creeks. At the southern end of the spit barrier (Saboneses Point), a wide tidal delta composed of two main sandy lobes is developed at the mouth of Río San Pedro tidal channel (Fig. 8.1).

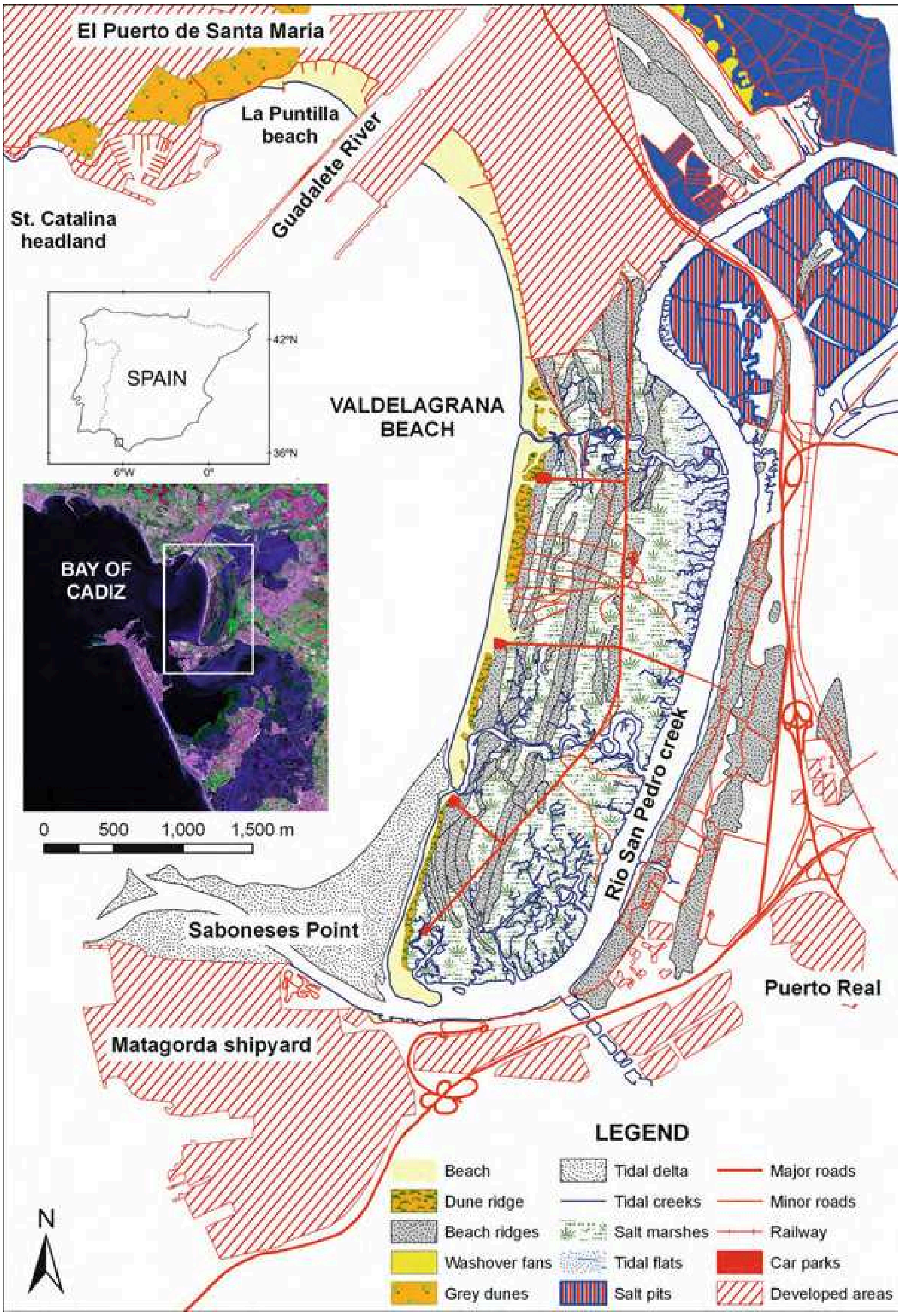

Fig. 8.1 Location and geomorphological sketch of Valdelagrana spit barrier

The beach is composed of fine quartz sand, and it shows a typically dissipative profile about 250 m wide in the northern and central sectors of the spit. Intertidal slope tends to decrease southwards, and at the southernmost end the profile turns ultradissipative and is nearly 500 m wide; here the beach almost transforms into a tidal flat as it connects to the tidal delta at Saboneses Point (Benavente et al. 2006).

Valdelagrana is located in the centre of a heavily populated area, the Bay of Cádiz, with over 400,000 inhabitants. The spit barrier shows different levels of human occupation: the northernmost sector is densely urbanized and the beach is backed by a seafront, apartments and summerhouses, while the rest of Valdelagrana is part of a protected area, the Bay of Cádiz Natural Park. The only man-made structures in the natural area are a former road that ran N-S along the whole spit, with four transversal secondary junctions and small car parks next to the beach (Fig. 8.1). Most of these structures were dismantled in 2002 as part of a conservation programme of the Natural Park, with the aim of trying to restore the natural environment.

The area is located on a mesotidal coast according to Davies (1964), with a MSTR (Mean Spring Tidal Range) of 2.96 in Cádiz harbour (Benavente et al. 2007). Dominant winds blow from east to southeast and west to southwest directions, although the former is not significant in wave generation due to its short fetch. For this reason, prevailing sea and swell waves approach the coast from the west. The highest waves occur in winter associated with Atlantic low pressure systems, when they can reach heights of up to 4 m. However, over 70 % of annual waves are less than 1 m high, so the Cádiz littoral can be classified as a low-energy coast. Coastal setting and the prevalence of westerly waves determines longshore drift to generally flow in a SE direction.

8.3 Historical Evolution

A combination of methods was used to reconstruct the main phases of spit evolution and the possible causes of the changes. Data included detailed geomorphological mapping from aerial photographs spanning the last five decades, geoarchaeological analysis of settlements and their surroundings, historical documents, data from existing and new sediment cores, radiocarbon dating of samples taken from the cores and field inspection.

Strictly speaking, Valdelagrana is a beach-barrier generated over 3,000 years ago, which has experienced a complex evolution during historical times as a result of variations in the incident energy. Very energetic events, like strong storms and especially tsunamis, as well as human activity, have played a key role in the evolution of this area (Luque et al. 2002). Valdelagrana contains a series of historical beach ridges, more or less parallel to the present coastline. In the southern area, many of the ridges form hooks characteristic of spit ends, indicative of the prevailing longshore drift and wave refraction processes. Detailed mapping of ridges and hooks allowed the identification of a set of over 20 different prograding episodes (Rodríguez-Polo et al. 2009), with complex inter-relationships.

Since the eustatic sea level highstand was reached in the zone, about 5,300–4,800 year BP (Gracia et al. 2006), sea level has remained in a more or less stable position until present; this favoured the development of coastal prograding sedimentary systems. The oldest beach ridges in Valdelagrana date to 3,500 year

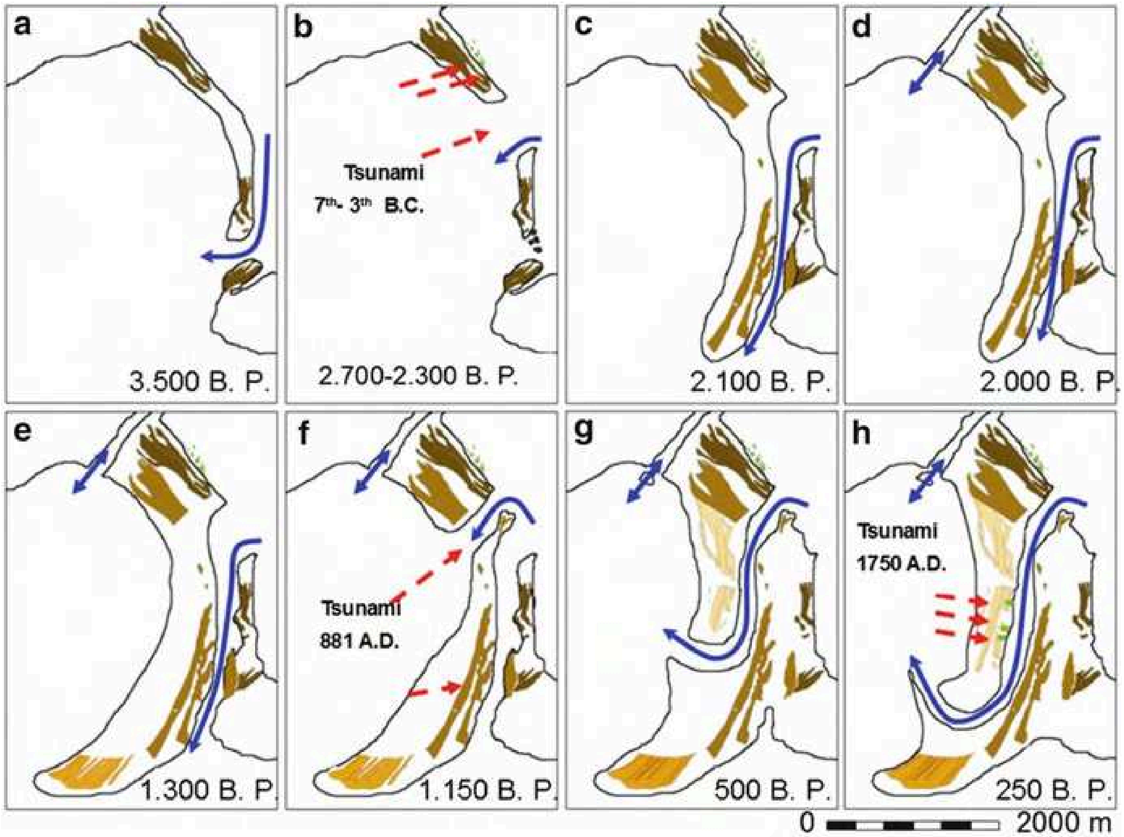

Fig. 8.2 Diagrammatical representation of historical evolution of Valdelagrana spit barrier. *Brown zones* indicate present remains of different sets of historical beach ridges

BP (Zazo et al. 1994), by which stage they were already occupied by humans (López Amador and Pérez 2013). This age is significantly younger than the oldest Holocene beach ridges in other nearby coastal prograding systems, such as Doñana (Goy et al. 1996). This apparent absence of older ridges in Valdelagrana has been interpreted as the consequence of an initial sedimentary infilling of the original Guadalete estuary, by which a slow aggradational process would have prevented the generation of coastal prograding bodies (Dabrio et al. 2000). Nevertheless, some new cores in the back-barrier marshlands seem to indicate that perhaps beach ridges formed earlier, approximately at the same time as in other nearby systems, but in Valdelagrana they were fossilized by subsidence and burial under marsh sediments. Other outcrops may have been eroded by lateral migration of the Guadalete River near its mouth, as revealed by the numerous abandoned channels and meanders found in its floodplain near the river mouth.

The southward growth of the first set of ridges caused the migration of the Guadalete River mouth in the same direction (Fig. 8.2a). During pre-Roman and early Roman times several very energetic events, probably tsunamis, affected the Gulf of Cadiz coast. Archaeological and sedimentary records point to events that likely occurred in the seventh and third centuries B.C. (Luque et al. 2002; Lario et al. 2010). Very probably, one or both of them broke the Valdelagrana ridges, opening a breach in the central-northern sector and destroying a significant part of the pre-existing sedimentary records. This can be deduced from the large gap existing in the central zone of the older set of ridges. This breaching surely caused the relocation of the river mouth into the central sector of Valdelagrana (Fig. 8.2b) as new, younger ridges began to form in an outer position, growing to the South and making the river mouth drift in this direction. The following stability period allowed the growth of new prograding ridges, from the third century B.C. onwards. The development of this episode is documented for the Roman Epoch (Fig. 8.2c).

About 2,000 B.P. historical documents briefly describe how a new artificial, straight channel was opened in the northern area to facilitate ship navigation and to control trade (Gracia and Alonso 2009). Archaeological remains in the zone have been used to confirm this opening (López Amador and Pérez 2013). This important intervention is also verified by several geomorphological evidences, like a minor NW-SE incision which can be continued at both sides of the channel, or the old meander imprints left by the river during previous stages, which draw a natural tendency of the channel to drift to the SE instead of flowing to the SW. The cutting, about 2 km long, generated a fluvial estuary with two active mouths, one in the North, near the present town of El Puerto de Santa María (Figs. 8.1 and 8.2d), which has maintained its location until the present due to continuous dredging works. The other mouth was located in the South, west of the present town of Puerto Real (Fig. 8.1), and it was finally closed by humans much later, in the eighteenth century, through works described in detail in different historical documents.

The intervention in 2,000 B.P. occurred at the time of maximum historical occupation in the Bay of Cadiz, during which several cities and villages developed, leading to the construction of roads, port facilities, coastal and fluvial hydraulic works (aqueducts, river and tidal channels, salt pits, etc.). From that moment on the sediment supply of the Guadalete River discharged directly into the coastal zone around Valdelagrana. This favoured a period of very rapid coastal progradation. In fact, radiocarbon dating of different ridges suggests a shoreline advance of over 1,000 m in only 800 years (Fig. 8.2d, e; Gracia and Martin 2009; Rodríguez-Polo et al. 2009). This progradation could have been affected by several historically documented energetic events, both of climatic and seismic origin, recorded in the Gulf of Cadiz (Campos 1992; Gutiérrez-Mas et al. 2009). According to historical records, a devastating tsunami affected the Gulf of Cadiz in 881 A.D. Dating of samples taken in Valdelagrana suggests that this event deeply eroded most part of the Roman-age ridges and opened a new breach (Fig. 8.2f), again in the central sector – the most vulnerable one according to its position, orientation and nearshore morphology. Sedimentary records of this event on the ridges indicate that they were directly exposed to the marine action and that the Guadalete River had never flowed to the west of this position (Gutiérrez Mas et al. 2009, Alonso et al. 2014). More recent historical maps (seventeenth century) show how the river flowed to the west of this point, as it does at present. Hence, it can be deduced that as a consequence of the 881 A.D. energetic event, a new capture of the southern river course occurred, which moved its mouth to the breaching point. Subsequent modal, low-energy conditions led to a rapid growth of new sedimentary ridges, which in this case developed as barrier-spits that migrated southwards; this can be deduced from the geometrical relationships between the new sets of ridges and the former one (Fig. 8.2g) As this new set of ridges grew, the southern river mouth also migrated in the same direction and progressively eroded part of the previous Roman ridges. Some remains of the ancient Roman ridges, not completely eroded by the southward drifting of the river mouth, can still be recognized in 1950s aerial photographs to the south of the present Río San Pedro creek (Fig. 8.1). These Roman ridges were destroyed in the 1970s and occupied by a shipyard.

In the eighteenth century a new human intervention deeply altered the fluvial dynamics of the Guadalete River. An artificial cut was excavated in 1721 in the inner marshlands that made the Guadalete river flow to the sea entirely through the Northern mouth, leaving the Southern one completely inactive (Baldera and Falcón 1987). This intervention had two purposes: increasing the water depth in the Puerto de Santa María harbour, of growing importance for its commercial activity with America at that time, and preventing the formation of wide intertidal sandbars in front of the Northern mouth (López Amador and Pérez 2013). As a result, the southern mouth transformed into a tidal channel, losing any significant sediment supply and the ability of active lateral migration, as it remains nowadays (Río San Pedro tidal creek).

In 1755, the devastating tsunami associated with the Lisbon earthquake, with waves about 8 m high in this zone (Campos 1992), flattened all the previous historical ridges (Fig. 8.2h). Two new transverse breaches, which abruptly cut all the previous ridges by forming small E-W microcliffs, could have been produced by this tsunami. These breaches affect recent ridges dated to 340 cal. year B.P. (Gracia and Martin 2009). Two minor tidal channels occupy the bottom of these breaches and at present they form small tidal deltas that partly block longshore sediment transport. From then on, a new system of beach ridges developed in front of the historical ones, although aerial photographs from the last six decades suggest that the rate of progradation has been much lower than in previous historical epochs (Martínez del Pozo et al. 2001).

8.4 Recent Behaviour

Recent changes occurred in Valdelagrana spit barrier were assessed using 14 sets of aerial photographs and orthophotographs spanning the period between 1956 and 2008 (Del Río et al. 2009, Rodríguez-Polo et al. 2010). GIS tools were employed to georectify the photographs and digitize the high-water line or HWL (Crowell et al. 1997) and the dune toe (Moore and Griggs 2002). Detailed rates of change were calculated by linear regression on shore-normal transects drawn every 20 m along the spit, by means of the DSAS extension for ArcGIS® developed by the USGS (Thieler et al. 2005).

Shoreline behaviour in Valdelagrana over the last five decades shows very clear patterns, with marked contrasts between both ends of the spit (Fig. 8.3) (Del Río

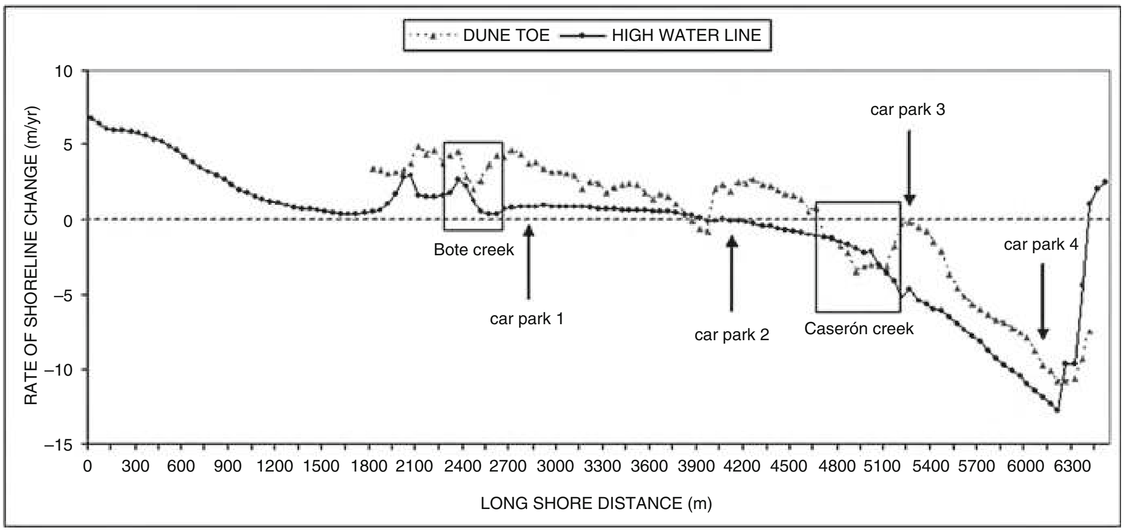

Fig. 8.3 Shoreline change rates along Valdelagrana spit between 1956 and 2008. The left section of the graph corresponds to the northern sector of the spit, i.e. the urban zone where dunes are absent. For reference purposes, the areas affected by tidal creek dynamics have been highlighted, as well as the location of the car parks

et al. 2009). The evolution of the HWL reveals a strongly accreting trend in the northern section, with average rates of up to 6 m/year in the shadow zone of the Guadalete river jetty that gradually diminish southwards. The accretion rate was maximum between 1977 and the late 1980s. The central portion of the spit exhibits generally low variations, except at points affected by local migration of the minor tidal creeks. In contrast, the southern spit end has recorded extreme erosion, with rates between −6 m/year immediately to the south of the second creek and up to −14 m/year in front of the southernmost (dismantled) car park at Saboneses Point (Del Río et al. 2009).

These trends are also reflected in the evolution of the dune toe (Fig. 8.3), with an average accretion of 3.2 m/year in the northern and central zones and important changes in the areas adjacent to tidal creeks. A new dune ridge developed immediately to the south of the first parking lot from 1977 onwards, revealing the intrinsically stable character of this sector (Benavente et al. 2006). The inflection point between the accretionary and erosive zones is located in the second creek. Here a change in the position of the inlet was recorded between 1977 and 1982, possibly related to the breaching of the dunes by a very energetic storm event; this could have occurred in February 1979, when wave height exceeded 7 m according to SIMAR-44 dataset from the HIPOCAS project (Del Río et al. 2012).

As with the HWL, the dune toe also recorded extreme recession at the southern spit end (Figs. 8.3 and 8.4). Here average retreat rate for the last decades was −7.7 m/year, increasing southwards up to a maximum of nearly −12 m/year in front of the last car park (Del Río et al. 2013). This erosion around Saboneses Point has involved the loss of a 200–450 m wide strip of beach, dune and salt marsh areas (Rodríguez-Polo et al. 2010) (Fig. 8.4). Modern dunes in this zone are low, narrow

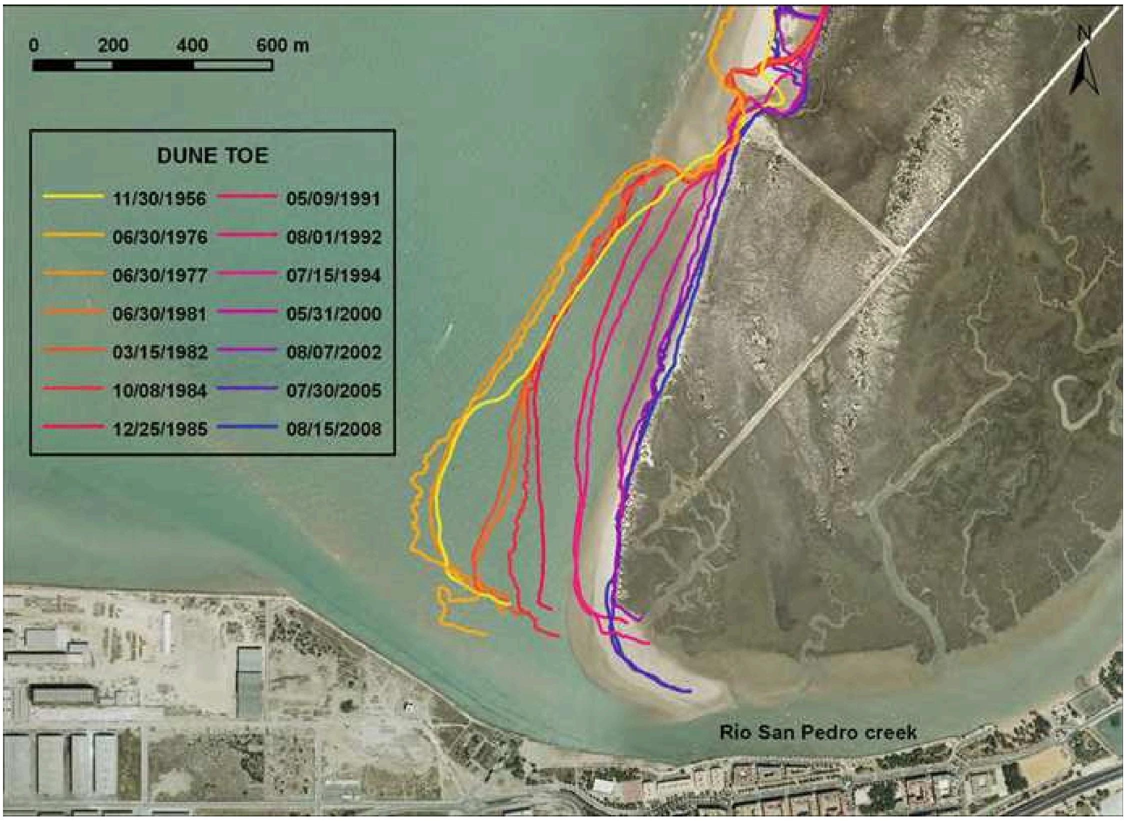

Fig. 8.4 Changes in the position of the dune toe at Saboneses Point along the study period (1956–2008). Note the initial stability of the shoreline until 1977, followed by very fast erosion until mid-1990s

and discontinuous, further increasing the vulnerability of this area to erosion, flooding and overwash processes in case of storms (Benavente et al. 2006).

Temporal analysis of shoreline changes reveals that stability and accretion dominated in the dunes between 1956 and 1977; by that time, however, the beach had already started to erode at Saboneses Point. Dunes turned then rapidly to erosion, and maximum dune retreat took place in the period 1977–1982 (up to 30 m/year), and at Saboneses Point also between 1982 and 1992 (Benavente et al. 2006) (Fig. 8.4). These periods of maximum dune toe erosion coincide with the maximum HWL accretion at the northern zone of Valdelagrana. Over the last years this accretion has stopped and dune erosion in the southern sector has greatly slowed down, although recession rates were between −1.5 and −6 m/year in the period 2002–2008.

From the above data it is clear that recent behaviour in Valdelagrana spit barrier represents an example of fast response to anthropogenic changes in sediment budget. In this way, the evolution of this zone over the last five decades has been determined by three main factors (Del Río et al. 2009):

(i) The building of three dams in Guadalete river basin between 1956 and 1977 probably contributed to the initiation of beach retreat at the southernmost end of the spit, due to their effect of fluvial sediment trapping (Rodríguez-Polo et al. 2010). Two bigger dams were built in the 1990s, but their effect is overlapped by that of other factors affecting the area (see below).

(ii) The timing of building and lengthening of the jetties located at the mouth of Guadalete river (Fig. 8.1) is clearly related to the patterns of shoreline change in the study zone (Martínez del Pozo et al. 2001; Rodríguez-Polo et al. 2010). In 1956, before these structures were built, the shoreline of both La Puntilla and Valdelagrana beaches constituted a single unit; the planform shape fitted a log-spiral function (Yasso 1965) or a parabolic bay equation (Hsu and Evans 1989), being adapted to wave conditions according to the static equilibrium model of Terpstra and Chrzastowski (1992) (Martínez del Pozo et al. 2002). The southern beach started eroding in the mid-1970s when the jetties were built, while the dunes started eroding a few years later and recorded the strongest erosion when the jetties were lengthened in the early 1980s (Fig. 8.4). In this headland-bay system, the main effect of the jetties was the shifting of the upcoast control point of the log-spiral, which is the point from which wave diffraction starts (Terpstra and Chrzastowski 1992). The building and especially the lengthening of the jetties moved this control point southwestwards, so the planform shape of the spit barrier had to rotate to adapt to these new wave conditions, by eroding in the southern end and accreting in the northern (Martínez del Pozo et al. 2002). Other impacts of these structures include the interruption of longshore drift, that generated massive sand accumulation at La Puntilla beach (Del Río et al. 2013), and the injection of fluvial sediments into the outer Bay of Cádiz, where transport by tidal ebb currents prevents sediments from reaching Valdelagrana spit end. Overall, this produced a transformation of the system from a sand spit controlled by longshore drift to a swash-aligned beach controlled by wave refraction.

(iii) The land reclamation performed in 1976 for the building of Matagorda shipyard, which is located south of Río San Pedro inlet, significantly affected the evolution of Saboneses Point (Martínez del Pozo et al. 2001). Tidal hydrodynamics in the area were completely changed by this reclamation, as the mouth of the Río San Pedro tidal channel was narrowed, thus increasing the velocity of the ebb flow currents. This triggered erosion of its southern bank, where defence works and artificial nourishments had to be performed (Herrera et al. 2010). As a consequence, the tidal delta, which is mainly formed by sediments eroded from Valdelagrana beach, started developing and growing westwards (Martínez del Pozo et al. 2001); at present it covers an area of about 2 km^2 and constitutes a problem for operations at the shipyard.

In the last few years it seems that Valdelagrana shoreline is reaching a new equilibrium with the surrounding conditions of sediment supply and forcing agents, especially wave patterns, as northern accretion has stopped and southern erosion has greatly slowed down. However, coastal recession on the southern section of the spit is still significant, especially after energetic storm seasons such as the winter of 2009–2010 (Rangel-Buitrago and Anfuso 2011).

8.5 Present Dynamics

A 3-year program of topographic beach monitoring was performed to evaluate short-term morphodynamic behaviour of Valdelagrana beach. The surveys were performed on a monthly basis on shore-normal topographic profiles distributed along the whole spit, extending from the dune toe or the seafront to a depth equivalent to the mean spring low water level (Gracia et al. 2005). Beach sediment samples were collected and analysed by dry sieving. Wave data used to calculate beach morphodynamic parameters were obtained from the offshore buoy “Cádiz” (National Ports Authority), located at a depth of 20 m about 10 km from Valdelagrana. Present dynamics of the tidal delta at Saboneses Point was assessed by detailed DGPS surveys and deployment of current meters and pressure transducers on the delta (Rodríguez-Polo 2009).

Beach monitoring reveals a clear alongshore (north-south) gradation in morphological and sedimentological parameters. Beach profile morphology is visually dissipative in the northern sector, with a gentle slope around 2.3 % and some intertidal bars (Anfuso et al. 2006). Beachface slope gradually decreases southwards, and in the southern sector of the spit the profile morphology is visually ultradissipative and resembles a tidal flat (slope 0.7 %) without bars, cusps or other features (Gracia et al. 2005). Beach profile variability also shows a north-south gradient, with moderate seasonal changes occurring in the northern sector, while the southern profiles show a continuously retreating trend (Fig. 8.5) without any significant seasonal variations. In fact, dune disappearance was recorded at Saboneses Point during the study period, as well as outcropping of fossil saltmarsh

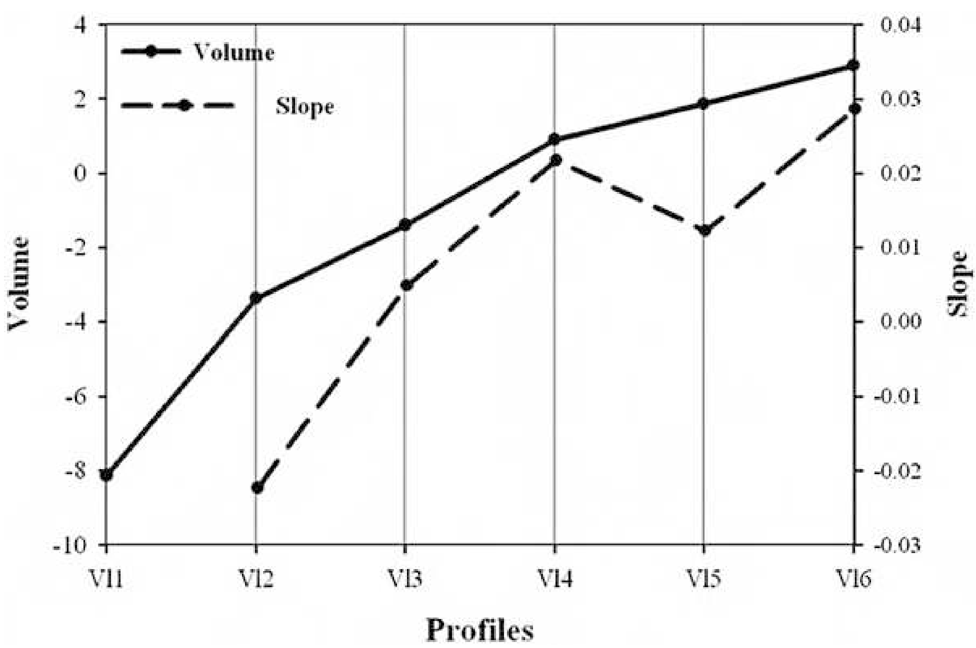

Fig. 8.5 Evolution of beach profile volume (monthly rate of volume change in cubic meters per linear meter of beach) and intertidal slope at Valdelagrana beach during the study period. Note that Vl1 is located at Saboneses Point and Vl6 is located at the northern end of the study area

sediment in the intertidal zone after storm periods, clearly indicating landward recession of the spit. Similarly, volumetric changes reveal a slightly accreting pattern on the northern profiles, while the southern area displays an erosive trend (Gracia et al. 2005) (Fig. 8.5). The areas close to the tidal creeks are greatly influenced by inlet-related processes and so they differ from this general behaviour.

Regarding sediment characteristics, the beach is composed of well-sorted fine sand; average grain size (D_{50}) is 0.16 mm, with a slight decrease in the southward direction. According to Benavente (2000), this can be related to the differential transport of finer sediments by longshore drift (Komar 1998) from the source area, i.e. the Guadalete River. Grain size patterns in the southern profiles show a distinct increase in mean grain size, indicating erosive processes.

As for beach morphodynamic state, Valdelagrana is clearly dissipative according to classic models of Wright and Short (1984) or Masselink and Short (1993). No changes in morphodynamic state were recorded during the monitoring program (Anfuso et al. 2006). However, and as mentioned above, gradients in beach slope and grain size indicate the northern area is closer to intermediate states while Saboneses Point shows some typical ultradissipative morphologies (Benavente 2000).

From the above information it can be stated that present morphodynamic behaviour in Valdelagrana is determined by three main factors: tidal influence, sediment supply and evolution of beach planform shape, the two latter being highly dependent on human activities. In this respect, strong tidal currents are responsible for generating beach morphologies more typical of macrotidal environments, despite the study area being mesotidal (Benavente et al. 2007). On the other hand, there is a gradient in beach characteristics and hence morphodynamic behaviour as the distance to the sediment source increases. Sediment supply is an important factor controlling how the beach reaches equilibrium planform shape, so the aforementioned decrease in sediment delivery over the last decades due to anthropogenic interventions would mean that the beach has not reached equilibrium yet. In fact, it can be stated that if the beach was in equilibrium, shoreline at the distal zone of the Zeta-bay (close to Saboneses Point) would be swash-aligned so there would not be any longshore drift or gradient in morphodynamic variables (Hsu et al. 1989). Therefore, medium-term anthropogenic interventions in Valdelagrana sediment budget have also triggered changes in present-day beach dynamics, as shown in the evolution of beach profiles, which are stable or accreting in the northern sector and clearly erosive in the southern one (Fig. 8.5).

As mentioned above, tidal influence also plays a significant role in the observed behaviour, since the gentle beach slope at the southern sector is related to strong tidal currents, which are not taken into consideration by models of Zeta bay planform evolution. These currents have speeds above 50 cm/s at the mouth of Río San Pedro tidal creek (González et al. 2010). As a consequence, in Valdelagrana beach the relative importance of wave energy gradually decreases southwards due to the presence of the ebb tidal delta, while the importance of tide energy increases, determining contrasting beachface morphologies and an ultradissipative profile in the southernmost sector (Benavente et al. 2007).

The development and growth of the tidal delta at Saboneses Point greatly influences beach behaviour. On one hand, wave dissipation on the delta determines the beach at the southern end of the spit being a very low-energy area, similar to the estuarine beaches described by Nordstrom and Jackson (1992), where the upper intertidal zone works as a proper beach but the lower intertidal shows a tidal flat behaviour. During high-energy storm conditions, erosion of the beach profile occurs by parallel retreat so that shoreline recession is recorded but beach slope remains unchanged (Rodríguez-Polo 2009).

On the other hand, water flow on the tidal delta is directed through two main channels: a main one running WNW-ESE close to Matagorda shipyard breakwater, and a secondary one running NNE-SSW in a shore-parallel direction at Saboneses Point. Current velocities in the main channel are around 60 cm/s and the highest velocities are recorded during ebb tide, while in the secondary channel they reach 80 cm/s during the flood tide, due to the coupling between the tide and prevailing wave direction and hence longshore drift. As a consequence of this, the secondary channel probably contributes to the scouring and erosion of the lower intertidal beach at this area (Rodríguez-Polo 2009).

8.6 Conclusions

Valdelagrana spit barrier is a clear example of multi-scale anthropogenic disruption of natural coastal behaviour. A variety of geomorphological and morphodynamic changes, including particular patterns of shoreline evolution, have been triggered by human activities in the area since Roman times. These are superimposed on other important natural sources of coastal change, such as energetic storms and tsunami events.

On the historical scale, major anthropogenic interventions occurred in Roman times and in the 18th century, and were focused on improving navigation in the Guadalete estuary. They generated massive progradation of beach ridges and the isolation of the Río San Pedro as a tidal channel, respectively. During the second half of the twentieth century, the building of two jetties at the river mouth and the reclamation works performed south of Río San Pedro produced significant beach accretion at the northern sector of Valdelagrana and extreme shoreline retreat at the southern sector, as well as the development of a wide tidal delta at Saboneses Point. The changes in spit dynamics generated by these interventions could still be noticed on beach profile behaviour over recent years.

Plans for future human interventions around Valdelagrana spit are lately being considered by national authorities. These include dredging the tidal delta, increasing harbour development both in Guadalete River mouth and Matagorda shipyard, and restoring the natural behaviour of old salt marshes which are currently dry. It is likely that dredging the delta would trigger erosion by waves due to the increase in shoreline exposure; nevertheless, present-day beach erosion at Saboneses Point is partly generated by the secondary channel of the delta during ebb tide, so the dredging could reduce this impact. Regarding the building of new harbour structures at Guadalete River mouth, they would produce a more efficient blockage of longshore sediment supply to Valdelagrana, as well as a further modification of the control point in the Z-bay planform. These processes would combine to intensify coastal erosion in the Southern end spit. As for the restoration of the reclaimed salt marshes, this would increase the tidal prism at Río San Pedro tidal channel, thus increasing the size of the tidal delta.

In any case, further research must be performed before any of the above interventions are executed, in order to avoid undesirable consequences in coastal stability. This research should be mainly focused on modelling wave propagation and longshore sediment transport in the coastal zone under different weather conditions, as well as assessing the volume of sediment supplied to the area by the Guadalete River.

In any case, it is important to note that besides human interventions, the long term evolution of Valdelagrana is also highly influenced by the short term erosion produced by storms during the most energetic winter seasons, so the storminess conditions in the future will be determinant in future shoreline evolution.

Acknowledgements This work is a contribution to the research group RNM-328 of the PAI and to the projects GERICO (CGL 2011-25438) and P10-RNM-6547.

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