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Coastal flooding hazard related to storms and coastal evolution in Valdelagrana spit (Cadiz Bay Natural Park, SW Spain)

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Abstract

Mapping of coastal inundation hazard related to storms requires the combination of multiple sources of information regarding meteorological, morphological and dynamic characteristics of both the area at risk and the studied phenomena. Variables such as beach slope, storm wave height or wind speed have traditionally been used, but detailed geomorphological features of the area as well as long-term shoreline evolution trends must also be taken into account in order to achieve more realistic results.

This work presents an evaluation of storm flooding hazard in Valdelagrana spit and marshes (SW Spain), considering two types of storm that are characteristic of the area: a modal storm with 1 year of recurrence interval (maximum wave height of 3.3 m), and an extreme storm with 6–10 years of recurrence interval (maximum wave height of 10.6 m), both approaching the coast perpendicularly. After calculating theoretical storm surge elevation, a digital terrain model was made by adjusting topographic data to field work and detailed geomorphological analysis. A model of flooding extent was subsequently developed for each storm type, and then corrected according to the rates of shoreline change in the last decades, which were assessed by means of aerial photographs taking the dune toe as shoreline indicator.

Results show that long-term coastline trend represents an important factor in the prediction of flooding extent, since shoreline retreat causes the deterioration of natural coastal defences as dune ridges, thus increasing coastal exposure to high-energy waves. This way, it has been stated that the lack of sedimentary supply plays an important role in spatial variability of inundation extent in Valdelagrana spit. Finally, a hazard map is presented, where calculated coastal retreat rates are employed in order to predict the areas that could be affected by future inundation events.

Keywords: Floods; Storm surges; Hazard assessment; Coastal erosion; Spain; Cádiz Bay

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1. Introduction

Flooding of coastal lowlands by ocean waters is mainly generated by storm action that makes sea level rise above the ordinary tide level. This water surface elevation is referred to as "storm surge" and consists of two main components. Strong winds blowing onshore over the ocean's surface pile up water on coastal areas ("wind setup"), while low atmospheric pressure tends to pump up ocean surface in an inverse barometer effect ("barometric setup"). In addition, a third concurrent factor is the increased wave breaking height, resulting in a water level increase in the surf zone ("wave setup"), reaching areas further inland than normal waves. The combination of storm surge and wave setup can

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result in occasional extreme wave runup overtopping dune ridges or coastal defences, particularly when storms coincide with astronomical high tides.

Storm surges pose the greatest natural threat to coastal communities, being the world's foremost natural hazard in terms of property devastation and lives lost (Murty, 1988). Potential consequences of storms create the need for tools that enable recognition of zones vulnerable to coastal flooding hazard. All of the above cited factors have been modelled separately with reasonable accuracy (Cheung et al., 2003) and the resulting information constitutes the basis for hazard mapping. An important point when plotting flood hazard maps is the accuracy of the topographic base and its adjustment to the real geomorphological coastal features.

Nevertheless, it is not only a matter of topography and a sea level height increase. Coastal evolution, especially coastal retreat, may introduce long-term morphological changes that strongly influence flood frequency and intensity. In retreating coasts the higher hazard zones will gradually shift landward unless shoreline stabilisation measures are implemented. Thus, the evaluation of impacts requires the landward projection of hazard areas based on local erosion rates. Dean and Malakar (1999) drew flood hazard lines starting from the Federal Emergency Management Agency (FEMA) data and applying shoreline information from ancient maps and charts for establishing long-term erosion rates. However, ancient maps for estimating erosion rates may not be the most appropriate basis due to their low accuracy and antiquity, since coasts may show a rapid response to very different natural processes or human interventions. Thus, vertical aerial photographs should be used in order to calculate more recent and realistic coastline trends.

The present work deals with the study of flood hazard due to storms in Valdelagrana spit and marshes (Fig. 1), one of the most vulnerable coastal areas within the Cadiz Bay, where no previous study has been made on this topic. The aim of the work is to elaborate a potential flood hazard map for both extreme and modal storm events. Its elaboration is based not only on the modelling of the main storm surge components, but also on the long-term coastline evolution of the spit obtained from different aerial photographs. Topographic data taken on the field and detailed geomorphological mapping helped to obtain more realistic flood hazard maps. Although no direct sea level height measurement could be made during real floods, oblique aerial photographs taken during a modal flood event served for comparing expected and real flooded areas.

2. Study zone

Valdelagrana spit constitutes a well-developed, N–S oriented sandy body that runs from the Guadalete river mouth to the San Pedro tidal creek outlet (Fig. 2). This tidal creek historically constituted a second active mouth of the Guadalete river and was artificially disconnected from the main fluvial channel in the 18th century. At present the spit has a total length of 7 km and an average width of 1.5 km. Since the beach is strongly restricted by groins and hard structures, it can be broadly considered as a littoral cell. Prevailing winds approach the coast from the West. Swell waves are dominant and come from the W and SW. As they are refracted around the Cadiz tombolo (Fig. 1), wave fronts finally become parallel to the coastline and as a consequence Valdelagrana is a mixed form between a spit and a swash-aligned barrier.

Longshore currents, directed to the South, are significant only when wave fronts approach the coast from the NW and WNW, usually associated to storms (average significant wave height about 1 m, Benavente et al., 2000b). In such a case, sediments supplied by the Guadalete river and those eroded from the beach accumulate in the southern spit end and form a wide (2 km^2) tidal delta in the San Pedro tidal creek outlet. This is a mesotidal coast with a mean tidal range of 2 m. Flooding tidal currents inside Cadiz Bay run from NW to SE near the coastline and favour accumulation of fine sediments on the southern spit end. Ebbing tidal currents focus on the central part of the Bay and flow towards its entrance (Parrado et al., 1996), making the tidal delta outer lobes bend to the NW.

Valdelagrana spit is characterised by different morphosedimentary environments, ranging from sandy beaches and foredunes in the sea front, Holocene ridges and historical salt marshes in the centre, and mud flats (*slikke*) and present salt marshes (*schorre*) in the eastward front and to the NE (Fig. 2). The beach is composed of fine sand and shows typical dissipative profiles of about 250 m width in the northern and central parts. The intertidal beach slope tends to decrease southwards

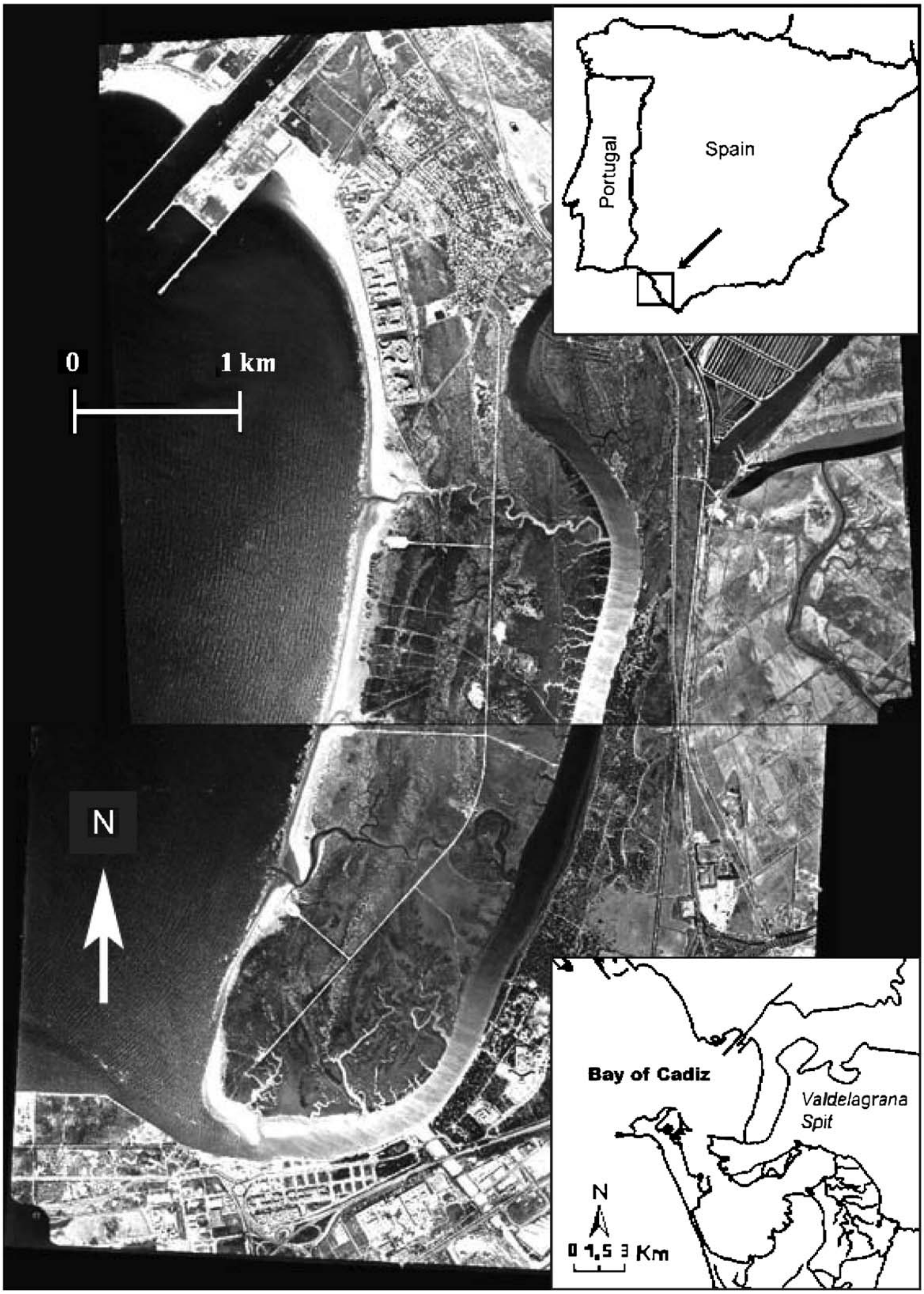

Fig. 1. Location of Valdelagrana spit barrier. Geometrically corrected photomosaic obtained from 1992 aerial photographs (photogrammetric flight by Andalusian Cartography Institute).

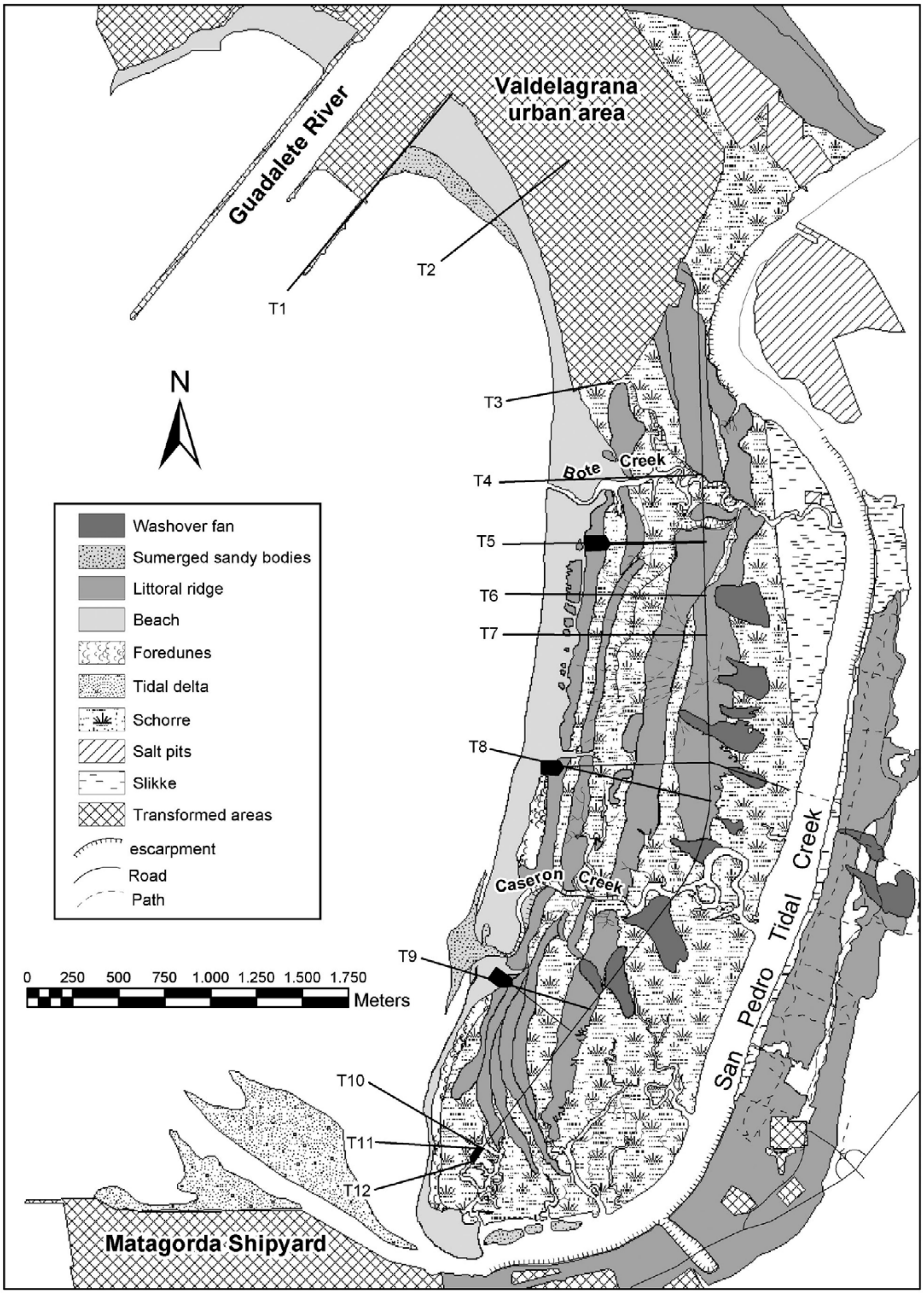

Fig. 2. Geomorphological map of Valdelagrana spit barrier. Solid lines represent photogrammetric transects (T1–T12).

due to the strong tidal currents acting on the San Pedro tidal creek (Benavente et al., 2000a). As a consequence, despite the general low wave energy recorded in the zone, beach profiles turn ultradissipative in the southernmost part, with a very gentle slope, a width of up to 500 m and very find sands, acquiring transitional characteristics between beaches and tidal flats. Foredunes form discontinous ridges that hardly reach 1.5 m high and 50 m wide. About 30% of the foredune surface is covered by vegetation, commonly *Ammophila arenaria*.

Four main Holocene beach ridges can be identified in the central part of the spit, running parallel to the present coastline (Fig. 2). Ancient, historical salt marshes develop between ridges, while ancient washover fans and erosional escarpments can be observed on the innermost littoral ridge (Martínez-del-Pozo et al., 2001), probably due to historical tsunamis (Luque et al., 2001).

The area shows different levels of human impact. The salt marshes located to the NE of San Pedro creek were dessicated in the 1950s for land reclamation. The northernmost part of the spit was heavily urbanised in the early 1970s, with apartments and summerhouses that were built very close to the beach, resulting in the destruction of the pre-existing natural environments, as a large promenade runs over ancient dunes and beach ridges. The rest of the spit is part of a protected area (Cadiz Bay Natural Park) with a great ecological importance. Only a narrow road runs along the whole spit length and shows four transversal secondary junctions with small car parks located close to the beach. As part of a conservation programme of the Natural Park, the road and car parks were dismantled in 2002 with the aim of restoring the natural salt marsh environment. A few bird observatories and a wooden footpath were built in order to promote the environmentally friendly use of the area by local residents. The programme also includes the partial recovery of the previously reclaimed salt marshes of the NE zone with the aim of increasing the tidal prism.

3. Methodology

The first step in the flood hazard study was the assessment of recent shoreline evolution of Valdelagrana spit. Although digital orthorectification of vertical aerial photographs improves shoreline evolution studies (Moore and Griggs, 2002), it eliminates tridimensional stereoscopic vision, thus rendering extremely difficult the identification of low-relief, low-contrast coastal features like foredunes. For this reason, and in order to identify low, poorly vegetated sand dunes, uncorrected photographs were used in the assessment of recent coastline evolution. Image distortions and displacement errors were minimised by working only at the central portion of the photographs (Anders and Byrnes, 1991). Errors related to tidal fluctuations were avoided by using the dune toe (limit backshore-foredune) as the feature representing shoreline position (Ojeda et al., 2002).

Photointerpretation was performed on a series of photographs from 10 photogrammetric flights carried out between 1956 and 2000 at scales ranging from 1:40,000 to 1:15,000 (Table 1). Stereoscopic measurements were made by means of a high-resolution prism stereoscope following the "point-measurement technique" (Moore, 2000). Exact scale was systematically computed by dividing focal length by flying height. Alternatively, when lacking detailed flying height information, exact scale was calculated by using the 1:10,000 topographical digital map (Andalusian Cartography Institute). Twelve transects normal to the shoreline were chosen along the spit length, each one linking a stable reference point and the shoreline (Fig. 2). Distances between reference points and foredune toe were measured on each aerial photograph and shoreline erosion/accretion rates were calculated.

Field data, 1:10,000 topographic maps and previous geomorphological maps (Martinez-del-Pozo, 2000) were used to accurately define the physiographic characteristics of the spit. Different elevations were subsequently assigned to each morphological feature by means of the topographic map. Such elevation data were positioned with respect to the zero level of the topographic map datum, i.e. ED50 (Spanish datum) and located in the field by topographic profiling using a total

Table 1
Photogrammetric flights used in this study

Flight date	Nominal scale	Performed by
1956	1:33,000	United States Army
1976	1:30,000	Unknown
1977	1:18,000	Spanish Ministry of Agriculture
1981	1:30,000	Unknown
1984	1:30,000	Spanish Army (CECAF)
1985	1:18,000	Spanish Army (CECAF)
1991	1:40,000	Spanish Geographical Institute (IGN)
1992	1:20,000	Andalusian Cartography Institute (ICA)
1994	1:15,000	Andalusian Government
2000	1:30,000	Andalusian Cartography Institute (ICA)

station. Topographical elevations and sea level height were measured at a certain time and sea level height was corrected by using local tidal tables. Local zero level in the area was established by computing data obtained after 3 years of monthly topographical profiling (Benavente et al., 2000b). After obtaining a common datum not influenced by meteorological variations, correlation between field elevation data, spit topography and geomorphology led to the construction of a Digital Terrain Model.

Water surface elevation due to storm surge was calculated by taking into account each one of the contributing factors, which were computed as follows:

Barometric setup: Provided that low pressures persist for a sufficient time span, water level increase is considered about 0.10 m for each 10 hPa drop below normal barometric pressure (1013 hPa), 1 cm per millibar. Sea level rise (dξ) was calculated

$$d\xi = (dP_a)/(\rho g), \quad (1)$$

where dP_a represents atmospheric pressure variation and ρ is the sea water density.

Wind setup: The effect of shore-normal winds piling up water on the coast was calculated by using the expression of Bowden (1983)

$$d\xi/dx = \tau_s/g\rho h. \quad (2)$$

In this formula, dx represents wave fetch from the centre of the low-pressure area to the coast, considered as 250 km in the study zone. This is the average distance between Valdelagrana and the centre of Cadiz Gulf, where low pressures are commonly located when winds blow perpendicularly to the coast and the area suffers the worst weather conditions. In the formula, h represents the depth of wave base level, which in Valdelagrana is about 20 m (MOPU, 1991), and τ_s is the tangential wind stress:

$$\tau_s = \rho_a C_D W^2, \quad (3)$$

where W is the wind speed, ρ_a is the air density and C_D is a drag coefficient whose value depends on wind speed (Bowden, 1983).

Wave setup: The increase of wave runup on the coast caused by high storm waves has been computed by means of the expression by Komar (1998), modified from an initial formula of Holman (1986), which includes both wave setup and runup, hence obtains a real estimate of maximum reach of waves

$$R = 0.36\, g^{0.5} H_0^{0.5} T \tan \beta, \quad (4)$$

where H_0 and T represent deep water wave height and period, respectively and tan β is the beach mean slope.

In this work two types of storms were considered: an average winter storm (February 2003), with a recurrence interval of about 1 year, and an extreme storm (January 1996), with a recurrence interval of 6–10 years (Rodríguez-Ramirez et al., 2003). In order to consider the worst possible conditions, data of atmospheric pressure, maximum wind speed and maximum wave height and period regarding both types of storms were used to compute water level rise along the spit, according to Eqs. (1)–(4). Due to refraction processes around Cadiz tombolo, final approaching wave directions at the coast for both cases can be considered as quite similar. Barometric and wind data recorded by the Spanish National Meteorological Institute (INM) for the 1996 storm were obtained from Rodríguez-Ramirez et al. (2003), while those of 2003 storm were directly compiled from the real-time information supplied by the INM. Wave data were recorded by the offshore buoy “Cadiz”, which is located near the study area (Maritime Climate Service, Spanish Ministry of Environment). Finally, information on beach morphology was derived from previous works (Benavente, 2000; Benavente et al., 2002a), from which an average winter intertidal beach slope was obtained: 0.03 for the northern part of the spit and 0.008 for the southern part. Such previous studies showed the limited morphological variability of Valdelagrana beach profiles between fair and winter weather conditions. Table 2 summarises the main data about dynamic variables regarding both types of storms.

Table 2
Dynamic characteristics of modal and extreme storms used to calculate storm surge components

	February 2003 (modal)	January 1996 (extreme)
ΔP	1021–1007 millibars	1024–1000 millibars
Maximum W	11.7 m/s	28 m/s
Maximum H_0	3.3 m	11.2 m
T	8.3 s	10.7 s
Wave approaching angle	260°	240°

The resulting height of water surface rise along the beach was added to the height of local zero level. In order to evaluate flooding hazard in the worst conditions, a spring tide situation was assumed by considering the height of mean spring tides in the area (MHWS), i.e. 3 m, which in fact was the real situation when the January 1996 storm hit the coast. Lines of flooding extent for each storm were obtained by superimposing the previously created DEM and sea level rise results.

4. Results

Table 3 shows the results of applying Eqs. (1)–(4) to modal and extreme storms. Difference in water level height reached by both storm types amounts to nearly 3 m and are mainly due to the role played by waves and winds, especially the latter, whose contribution to water level increase is more than 2 m higher in extreme storms than in modal ones. However, such water surface elevations only take place when storms approach the coast perpendicularly, as it usually occurs in Valdelagrana due to coastal orientation (Benavente et al., 2000a).

As shown on Table 3, the influence of variables affecting storm surge depends on storm intensity. This way, waves are the most important factors in 2003 modal storm, where they represent more than 50% of total storm surge elevation, while wind contribution represents about 30%. The opposite behaviour is observed in 1996 extreme storm, where wind effect reaches more than 60% of storm surge, while waves represent only 30% of total water surface elevation.

The reason for such differences can be found on formulae used by the storm surge model. Wave setup is defined by an asimptotic expression (Eq. (4)), while wind setup is controlled by an exponential expression (Eqs. (2) and (3)), so that low wind speed produces low wind setup values but as winds get stronger wind setup grows exponentially. This behaviour is due to the fact that wind setup is less influenced by nearshore morphology than wave setup. Increase in wave height for a given sea bottom slope shifts breaking waves offshore, which decreases its relative importance on total storm surge height. In the same way, steeper beach slopes cause wave setup to increase (Eq. (4)) due to the onshore shift in the position of breaking waves, which prevents wave energy dissipation.

Table 3
Barometric, wind and wave setup components contributing to elevation of sea level surface in average and extreme storms in Valdelagrana spit

	February 2003 (modal) $\Delta\xi$ (m)	January 1996 (extreme) $\Delta\xi$ (m)
Barometric setup	0.14	0.24
Wind setup	0.31	2.54
Wave setup*	NC: 0.51/S: 0.14	NC: 1.21/S: 0.32
TOTAL*	NC: 0.96/S: 0.59	NC: 3.99/S: 2.90

Error bounds in the figures are centimetric, since acceptable input data have one decimal point.

*NC: Northern and central sectors of the spit; S: Southern sector of the spit.

Fig. 3 shows the theoretical extent of the inundation caused by storms with a recurrence interval of about 1 year in Valdelagrana spit. The model illustrates how modal storms would flood the whole beach, as well as marshland areas including vegetated salt marshes (*schorre*), in an overall effect rather similar to that of spring tides in the area. Furthermore, flooding would be intensified in areas where lateral migration of tidal creeks or the effect of former washovers had previously damaged the dune ridges. As a result, those washovers would be reactivated, as shown by the indentations appearing in the foredunes and Holocene beach ridges (Fig. 3). Besides, one of the main consequences of storm surge is the increased wave runup, so that incoming waves can undermine the dunes and produce either escarpments or washover fans.

According to the model, extreme storms with recurrence intervals between 6 and 10 years would almost entirely flood the whole spit (Fig. 4), including beach, *slikke* and *schorre* zones. Only the highest areas of Holocene beach ridges would remain emerged above water level, while active dunes would be washed away by the sea. Valdelagrana urban area, located at the northernmost zone, would also remain theoretically safe in both cases due to its relatively high elevation above mean sea level, excepting the most recently urbanized zone, since it occupies a hollow between two beach ridges.

Another important point is the protecting effect of the tidal delta on San Pedro creek outlet, where the ultradissipative profile is responsible for a wave setup reduction that adds almost 1 m in 1996 storm and about 0.4 m in 2003 storm (Table 3). Nevertheless, this is not shown by the model (Figs. 3 and 4), because the low dune height in the southernmost part of the spit counteracts the protecting role of the tidal delta. Moreover, the overtopping of dune ridges by extreme storm waves would cause dune

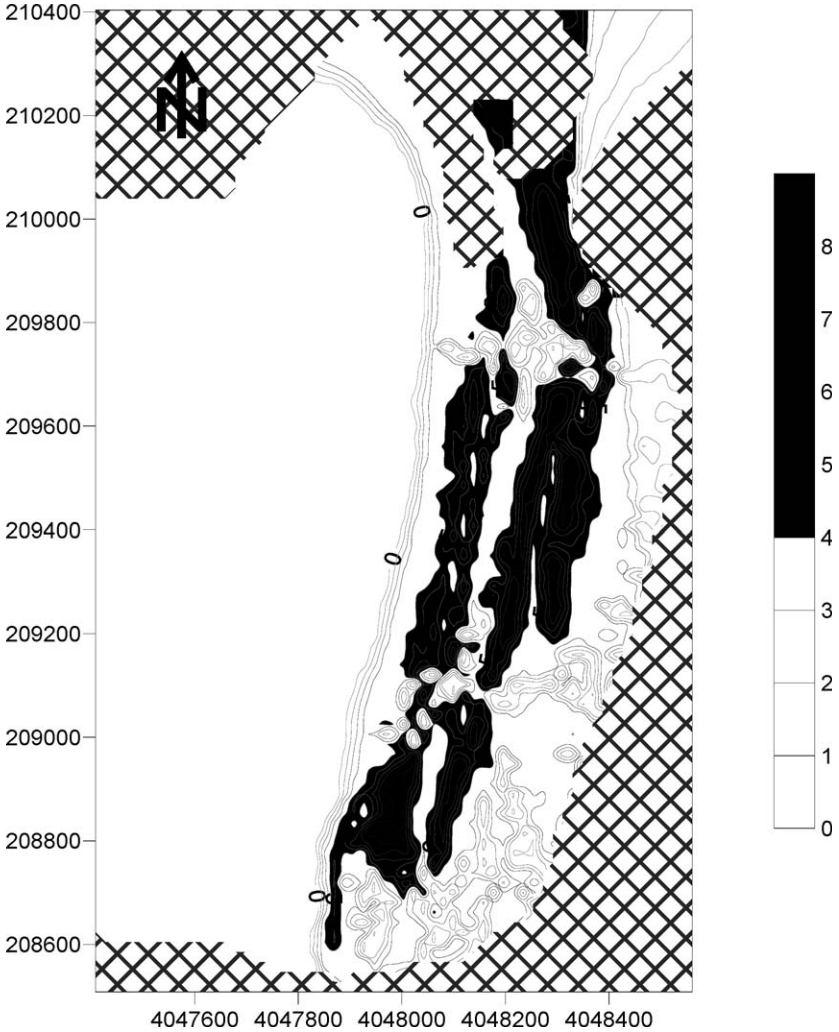

Fig. 3. Water elevation model for an average storm event (data from the 2003 storm). Contour lines in m above datum. Dark zones represent emerged areas during flooding.

flattening, also affecting the lowest areas of the outer Holocene ridges, while in the southernmost part the absence of littoral ridges backing the foredunes would induce the development of flame structures. Finally, a further effect of major storms would be the reactivation of ancient washovers on the most recent Holocene beach ridges.

The above-presented model would be useful to predict current inundation in case of modal or extreme storms. However, as explained on Section 1, shoreline evolution trends must also be taken into account in order to get a more realistic prediction of future floodings in the area. In this context, the analysis of vertical aerial photographs shows the morphological changes undergone by Valdelagrana spit in the last decades (Fig. 5). According to the results obtained, the spit can be divided into three sectors with different evolutive behaviour.

The northern part of the spit (transects T1–T3) has been subjected to intense human transformations in the last decades. The construction of two long jetties at the Guadalete river mouth between 1956 and 1977 and the subsequent changes in the hydrodynamic conditions of the area were accompanied by the progressive urban expansion since the 1960s, and in 1994 the northern sector of the spit was completely urbanized up to the limits of the Natural Park. Measurements made on this area show stability during the last two decades (Fig. 6). In this sense, promenade location was used for testing the precision of photogrammetric measurements and demonstrated the reliability of the

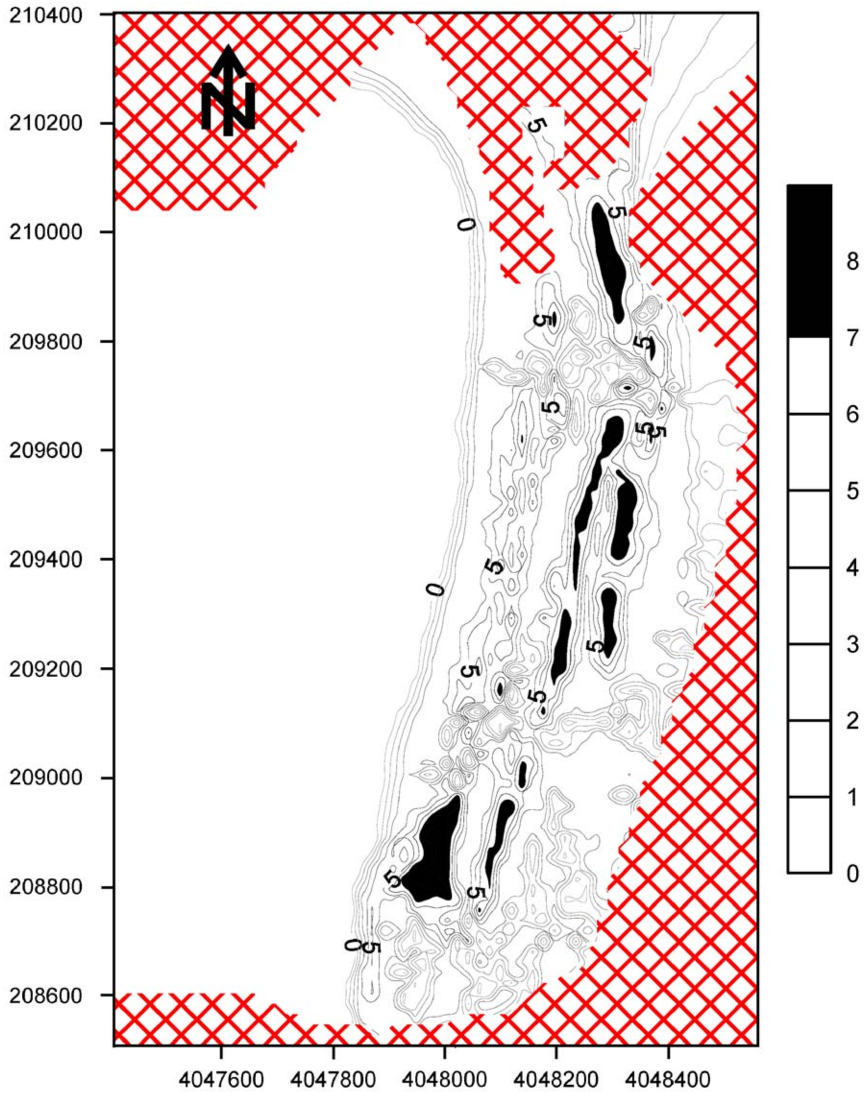

Fig. 4. Water elevation model for an extreme storm event (data from the 1996 storm). Contour lines in m above datum. Dark zones represent emerged areas during flooding.

method, since no changes were recorded in its position. Only minor intertidal features revealed a process of sediment accumulation in the shadow area next to the southern jetty.

The central part of the spit (transects T4–T9), limited between Bote and Caseron tidal creeks, is a natural area directly exposed to wave attack, with a straight and continuous coastline. No noticeable changes have been recorded in this sector during the studied period (Fig. 6), with the exception of a thin new dune ridge developed right to the south of a parking lot, and small changes observed around the mouth of a small tidal creek developed in the middle 1970s.

The southernmost sector of the spit (transects T10–T12) is the most dynamic one (Fig. 6) and has shown a dramatic response to changes induced by the jetties located in the Guadalete river mouth (Martínez-del-Pozo et al., 2001). After their construction, the first signs of erosion at the spit end appeared in 1976, with a sharp change in the beach morphology. The construction of Matagorda shipyard in 1977 considerably narrowed the San Pedro tidal creek outlet (Fig. 5), thus modifying hydrodynamic conditions in the area. From 1981 onwards shoreline retreat dramatically increased and began to affect the dune ridges and the salt marshes behind them. Erosion slowed down around 1991, when the

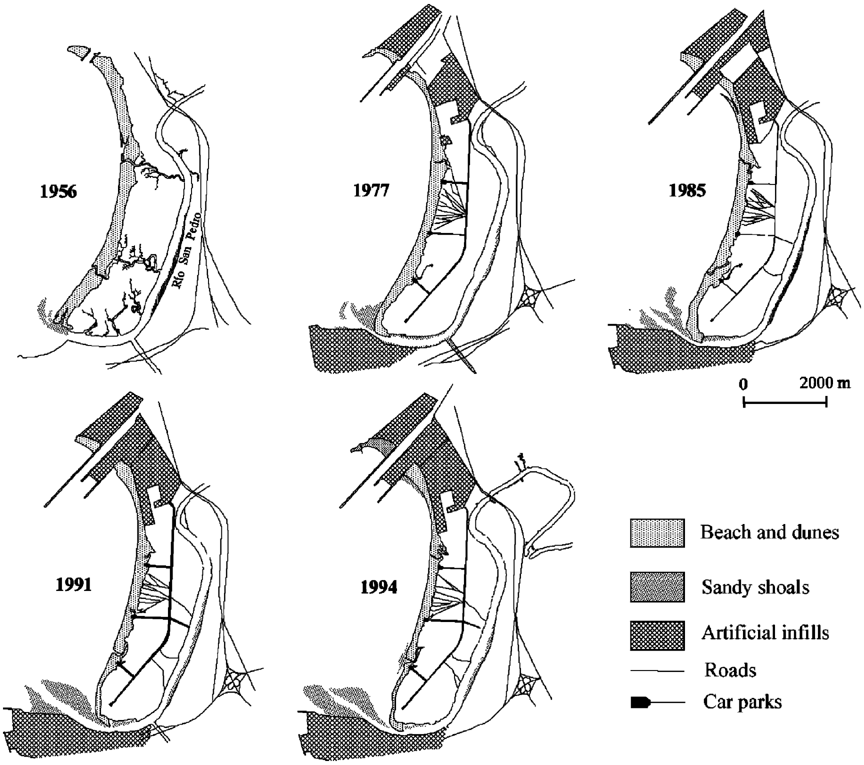

Fig. 5. Geomorphological evolution of the spit, from 1956 to 1994, obtained from aerial photographs.

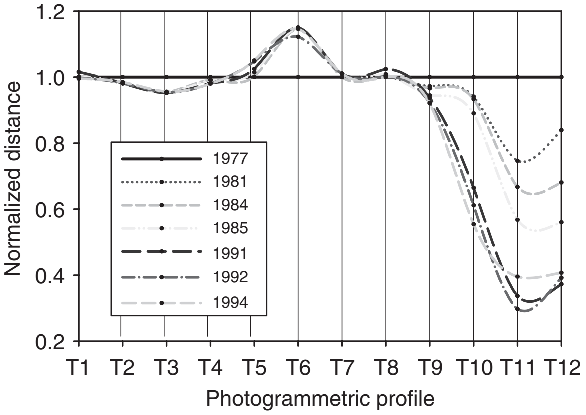

Fig. 6. Evolution of the photogrammetric transects between 1977 and 2000. Normalized horizontal distances are referred to the 1977 state. Values higher than 1.0 indicate accretion whilst lower values indicate erosion.

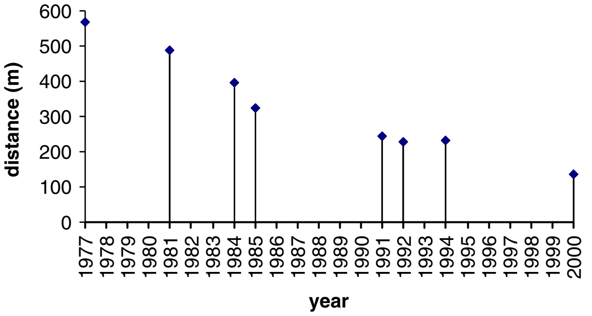

Fig. 7. Detailed evolution of profile T12 between 1977 and 2000. Distances are computed between a fixed reference point inland and the dune toe.

southern part of the spit reached equilibrium with the new hydrodynamic conditions imposed by the Guadalete river jetties and the Matagorda shipyard. Quantification of erosion on aerial photographs revealed that the southernmost point suffered a retreat of approximately 430 m in the period 1977–2000 (Fig. 7). Most important changes took place between 1977 and 1991, showing clear dune toe retreat at T10, T11 and T12 (Martínez-del-Pozo, 2000). From 1991 to 1995 the erosive trend experienced a sharp deceleration, coincident with a long period of fair weather during which no winter storms reached the study area (Rodríguez-Ramírez et al., 2003). That period concluded with the extreme storms that struck the coast in the beginning of 1996 (Fig. 8), which considerably increased shoreline retreat. Erosion rate in the period 1977–2000 at the spit end (transect T12)

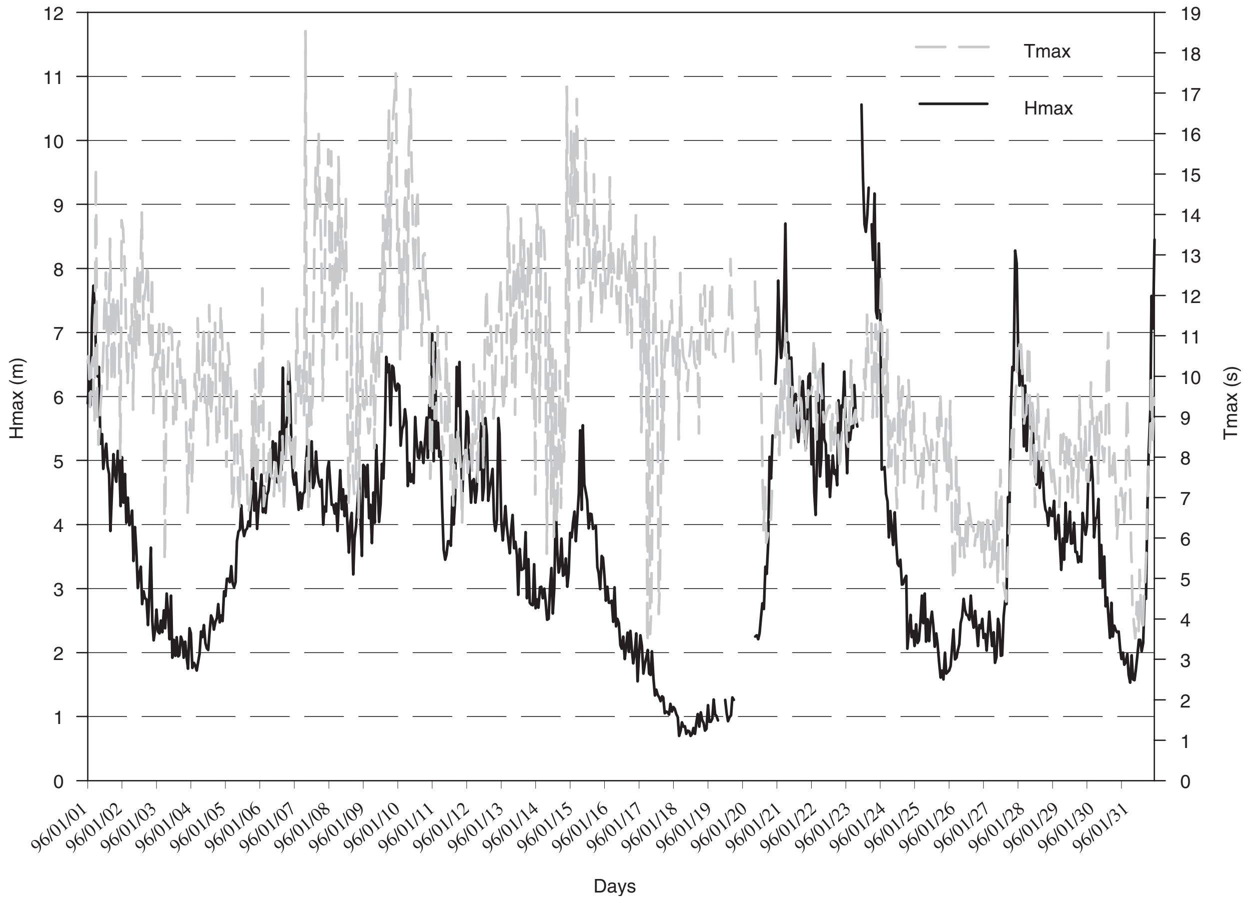

Fig. 8. Maximum wave height and period records for the January 1996 storm event.

averaged 27.56 m/yr, with the highest rates having been recorded between 1981 and 1985, around 39.24 m/yr.

Finally, the spit morphology showed clear differences between 1956 and 1994 (Fig. 5). The initial cumulative form, with a continuous, uniform beach and dune ridge, retreated and turned into an erosive morphology with a narrow beach, scarps on the foredunes and loss of dune ridges. Eroded sediments from beach and dunes were deposited in the foreshore to form the San Pedro tidal delta (Martínez-del-Pozo et al., 2001), a submerged sandy shoal presently exposed during the low tide.

The flooding hazard model can be validated by analysing the oblique aerial photographs on Fig. 9, taken during a modal storm in October 1998. They show an inundation quite similar to the flooding extent predicted by the model, with salt marshes almost entirely flooded and the Holocene beach ridges emerging above the water surface.

5. Discussion

The potential flooding risk is constituted by a combination of factors and variables that contribute in both space and time to the inundation of this coastal lowland. All these components must be summed up in order to perform a realistic flooding hazard map (Fig. 10), since the higher the number of factors considered in the analysis, the better the representativeness of the resulting map.

Spatial factors and variables are related to the topography of the area, a key issue in terms of the related hazard of shoreline flooding (Gares, 1990). Coastal topography is strongly conditioned by the nature of the different geomorphological features existing on the zone. A common value used in flooding hazard modelling is the dune volume necessary to provide protection against a given storm (FEMA, 1988, in Bellomo et al., 1999). However, it does not account for cross- and

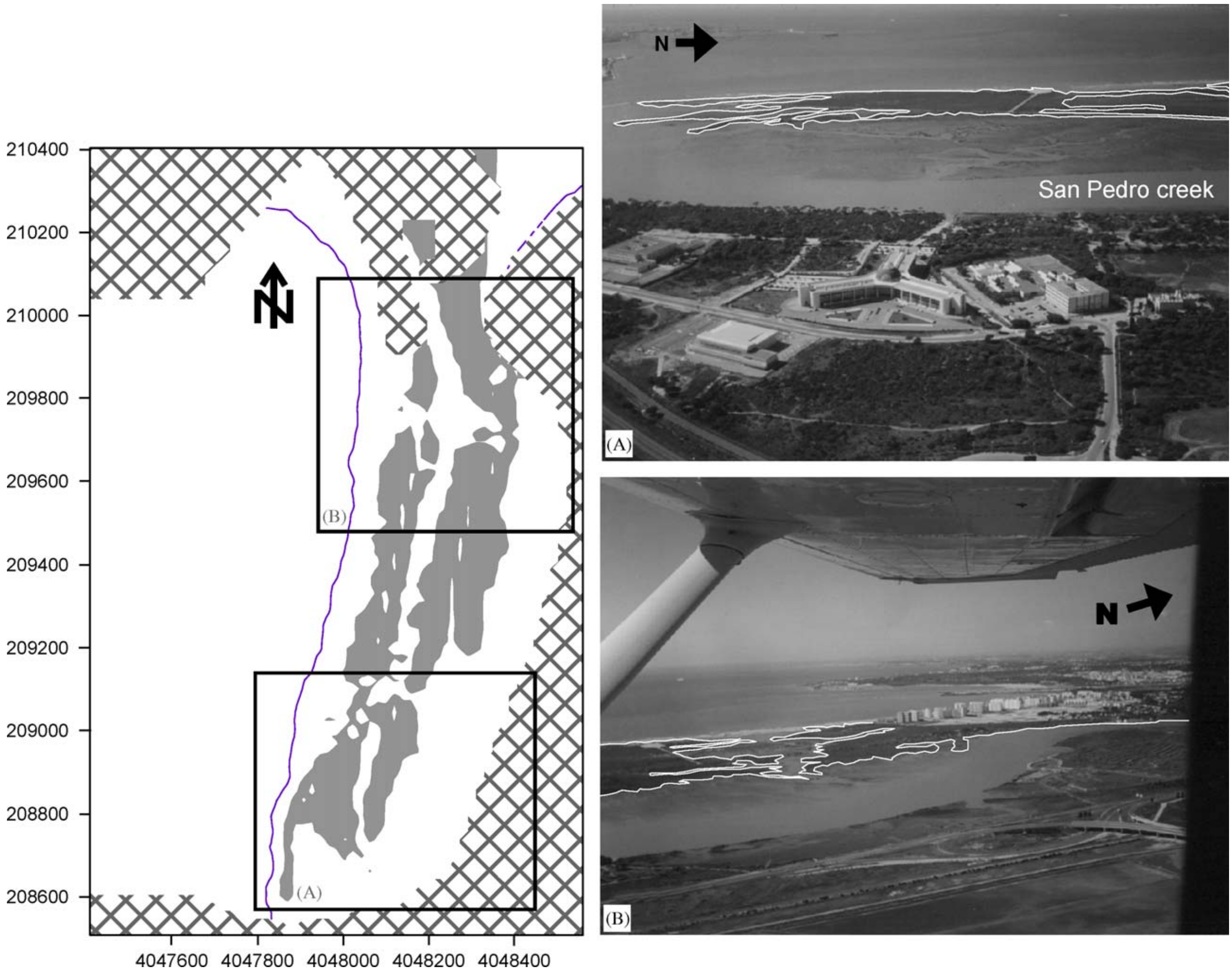

Fig. 9. Flooding photographs of Valdelagrana spit taken in October 1998 at high tide right after an average winter storm (courtesy of J.M. Abarca, Demarcación de Costas de Andalucía-Atlántico, Ministry of the Environment). Note Holocene beach ridges emerging above inundation level.

longshore variations that might exacerbate erosion and/or flooding at certain locations. This can be attained by means of combining the Digital Terrain Model and the detailed geomorphological map.

In Valdelagrana, contrasting geomorphological features induce a certain spatial distribution of the effects of flooding events. The gentle nearshore slope in the northern part of the spit provides a wide shoaling zone that prevents breaking waves from reaching the promenade, which together with the shoreline stability makes this sector likely to remain relatively unaffected by direct flooding due to storms. In the central zone of the spit salt marsh areas behind the dunes would undergo overall inundation through the tidal channels and dune ridges would experience overwashing and escarpment formation.

The southern spit end would suffer dune flattening where active dune ridges are not backed by Holocene beach ridges. Nevertheless, the southern tidal delta and the lower beach slopes at this point dissipate wave energy and reduce wave setup, decreasing flooding extent during minor storms, i.e. modal ones. Consequently, the southern part of the spit would not suffer permanent long-term damage, since major storms—the only ones capable of causing serious harm—have recurrence intervals long enough to let dune ridges and marshy environments recover from damages caused by previous storms (Benavente, 2000, Benavente et al., 2000a,b).

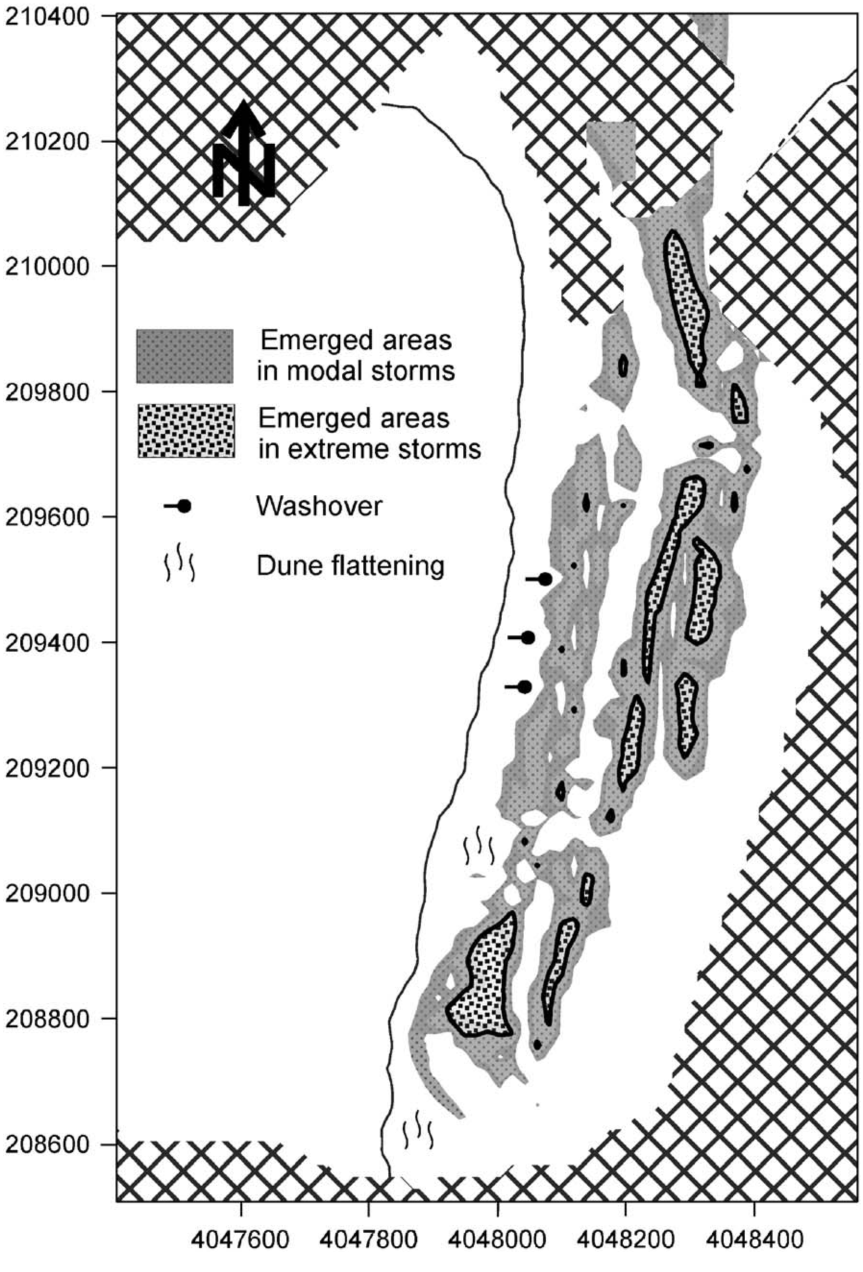

Fig. 10. Flood hazard map of Valdelagrana spit barrier.

Temporal scale of flooding is represented by the frequency of arrival of each storm type. As far as coastal flood is concerned, storm types or classes can be defined in terms of their associated maximum surge. The temporal occurrence of each storm class is then represented by their recurrence interval (Dolan and Davis, 1994) and the flooding hazard map in Fig. 10 includes the inundation extent for both analysed situations, modal and extreme storms. Another factor that must be considered is the possibility of such storms coinciding with equinoctial spring tides (4 m above mean low water level in Cadiz Bay). In this case the spit would be almost entirely flooded. However, such extreme tides occur around the end of March and the end of September, periods that are not concurrent with the typical storm period in the study area (November–January) (Benavente, 2000).

Concerning long-term evolution of Valdelagrana spit, on Section 4 it has been stated that the area presents a clear lack of sedimentary supply due to dam construction in the Guadalete river basin and to the construction and lengthening of the Guadalete river mouth jetties. These structures block sediment transport by littoral drift and also produce an injection of the fluvial sediments to the outer Cadiz Bay, substantially reducing the amount of sand redistributed by littoral currents along the spit (Martínez-del-Pozo, 2000). The decrease in sedimentary load of currents and waves approaching the southern spit end results in rapid erosion of the beach at that point (Fig. 11). Such erosion involves the narrowing and deterioration of active dune ridges, which have progressively been flattened and breached by overwashings and have nearly disappeared. Consequently this area, even though in theory sheltered by the San Pedro outlet sandy shoal, is actually at risk of suffering flooding so often as the rest of the spit. Therefore, it can be concluded that the combined effects of normal storm action and shoreline retreat would increase the frequency of inundation events and the ecosystem of the salt marshes behind the eroding dunes would be threatened.

At a medium-term scale, environmental deterioration at this zone would occur in several ways. Areas close to the active dunes would be progressively buried by their rollover (Fig. 11). The increased frequency of flooding episodes would gradually transform ancient, non-active marshland areas into active salt marshes. In the same way, areas of vegetated salt marshes (*schorre*) would in time transmute into tidal flats or non-vegetated salt marshes (*slikke*). Finally, the southernmost spit sector could eventually transform into a sandy flat, as it has occurred on other nearby spits (Benavente et al., 2002b).

Fig. 11. A level of marshland clays outcropping under the eroded beach at the southernmost zone of the spit after 1996 extreme storm.

Therefore, spatial and temporal aspects of potential flooding risk must be approached by including an evaluation of the change in shoreline position through time, so that hazard areas are projected landward according to local erosion rates. Consequently, Fig. 10 shows predicted flooding hazard for the next decade, considering a shoreline retreat of nearly 180 m at the southernmost point. In the long term, the predicted sea level rise due to climate change will undoubtedly increase the number and extent of coastal flooding events and, in a further step, should be also taken into account in the flooding hazard analysis (Pasaric and Orlic, 2001).

6. Conclusions

The analysis of coastal flooding risk in Valdelagrana spit shows the variable degree of vulnerability of a low sedimentary coast to storm-induced inundation according to the different geomorphological features existing on it: changes in intertidal beach slope, nearshore morphology, characteristics of dune ridges, etc. The presence of a well-developed dune ridge has demonstrated to be enough for effectively protecting the coast against modal storms. In case of less frequent severe storms, gentle nearshore slopes could theoretically protect the areas behind the beach and dunes. However, it is evident that storms are not the only agents involved in the flooding hazard of coastal areas: long-term shoreline retreat trends move the extent of inundated areas landward and predicted coastline positions must be calculated on the basis of their recent evolution.

The flooding hazard map presented in this work was initially based on the physical modelling of the main storm surge components, applied to two statistical situations: a probabilistic one by considering the modal storm, and a deterministic one by considering the most energetic storm recorded in the last decade. However, two important improvements have been introduced. Firstly, the digital topographic model was implemented by introducing field data about present topography associated with each geomorphological feature, resulting in a more realistic distribution of flooded areas. The resulting average-storm flooding map was validated from oblique aerial views of the zone taken during a modal storm event. Secondly, predicted coastline location for the next decade was drawn after calculating average erosion rates of the last 30 years, obtained from aerial photographs. This procedure served for better defining the consequences of coastal retreat in the redistribution of flooded areas in the forthcoming years. Both techniques helped to obtain a map more adjusted to reality.

Environmental policies being conducted at the area should take these issues into consideration. Efforts intended to recover natural marshland environments could prove useless if no action is taken to protect the spit against storms, namely by restoring active dune ridges that shelter the salt marshes behind them. In relation to this, the environmental recovery of previously reclaimed salt marshes to the NE of the San Pedro tidal channel would probably mean the erosion of the tidal delta and consequently the exposure of the southernmost point to direct storm wave action. This intervention would probably accelerate coastal retreat and flooding extent during storm events by increasing current speed along the San Pedro tidal channel, which would finally produce the disappearance of the low dune ridges that still exist on that area.

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