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ORIGINAL ARTICLE

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Vulnerability assessment of a retreating coast in SW Spain

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Abstract The present study assesses coastal vulnerability to erosion processes along a 23-km-long coastal sector that presents different morphological features and grades of human occupation. Seven photogrammetric flights, at different scales, were used for reconstructing the coastal evolution from 1956 to 2001. Several sources were compiled to assess human activities and land uses in the coastal zones that were mapped and divided into four different types. As a further step, coastal vulnerability to erosion was assessed combining the potential coastal retreat with land-use type. More than one third of the studied coast presents a very high–medium risk level and many human structures and activities at Sanlúcar village and La Ballena beach will be threatened by erosional processes in the near future.

Keywords Land use · Vulnerability · Aerial photos

Introduction

Coastal retreat is the landward displacement of shoreline because of marine erosion or flooding (Bird 1993). When these natural phenomena affect or pose a threat to any kind of human activities or infrastructures they switch over into a natural risk (Short 1999).

In the Gulf of Cadiz, coastal retreat mainly consists of shoreline erosion associated with storms that hit the coast during winter time (Rodríguez et al. 2003). Low probability hazards like tsunamis also exist (i.e. the one associated with the Lisbon earthquake, Luque et al. 2001).

In the study of littoral stability the quantification of erosion rate is very important because shoreline retreat takes place on a human time scale. Recorded data can be used to determine safe construction locations, elaborate land use plans, etc. Aerial photographs and satellite images are common tools that give information pertinent to environmental mapping and classification of coastal features, effects of storms, character of wave shoaling, etc. (Dickson 1990; Gorman and others 1998; Crowell et al. 1991, 1993; El-Asmar 2002; Berlanga and Ruiz 2002; Valpreda and Simeoni 2003). Coastal classifications have been also used to assess erosion risk, by using information on physical and ecological coastal features and human occupation. Such information was analysed through geographical information systems (GIS) and/or computer-assisted multivariate analysis (LOICZ 1995; Kelly 2000; Cooper and McLaughlin 1998). In this way, Dal Cin and Simeoni (1989, 1994) identified coastal stretches with similar physical characteristics, and Sánchez-Arcilla et al. (1998) evaluated Ebro delta vulnerability at different time scales. Coastal Zone Hazard Maps were prepared in USA (Bush et al. 1996) for coastal stretches affected by hurricane Hugo.

Eighteen procedures for coastal classification were reviewed by Cooper and McLaughlin (1998). Furthermore, according to Gornitz (1990) and Gornitz et al. (1993), the omission of demographic or economic factors from great parts of coastal classifications, potentially limit their effectiveness in the evaluation of vulnerable areas. According to these statements, McLaughlin, unpublished data and McLaughlin et al. (2002) developed a GIS-based coastal vulnerability index for the Northern Ireland littoral that takes into account socio-economic activities, coastal resistance to erosion and energetic characteristics.

Lizárraga et al. (2001) identified several coastal sectors of a homogeneous beach that lose recreational potential at Rosario, Mexico. The sectors were identified based on field data, such as beach width and morphology, because the beach was considered a protection for landward activities. As a further step, these authors combined beach reduction potential with the probability of landward structures to suffer damage and hence obtained coastal vulnerability types.

Recently, Pethick (2001) and Hansom (2001) proposed new, modern concepts on coastal management. According to these authors, coastal planners have an inadequate vision of erosion problems limited to a short-term view, but are not prepared for medium and long-term changes such as the replacement of a beach by a salt marsh.

In this work, a coastal vulnerability map was created by comparing data on coastal erosion and land uses along the littoral between Sanlúcar de Barrameda and Rota (SW Spain). Retreat and accretion rates were based on the study of aerial photographs of different scales and years, hence no indexes were necessary to evaluate coastal resilience to erosion. Land use values were estimated from several planning maps and catalogues of human activities (Agenda 21, Diputación Provincial de Cádiz 2003).

Studied zone

The studied littoral is 23-km-long and is limited in the North by Sanlúcar de Barrameda village, located at the Gudalquivir River mouth, and in the South by Rota village. Orientation of the coastline ranges from NE–SW in the Sanlúcar de Barrameda-Chipiona sector, to NNW–SSE in the Chipiona-Rota sector (Fig. 1).

The coast features sandy beaches with varying width, composed of quartz-rich fine and very fine sediments in the northern part, and fine and medium sands in the central and southern parts. Beaches are backed by dunes and cliffs cut into Pliocene and Pleistocene deposits, essentially composed of sands and silts in the northernmost part of the littoral and clays and silts in the Chipiona-Rota littoral. Cliff retreat exposed a rock shore platform, quite extended in the foreshore and nearshore zones.

According to Muñoz and Enríquez (1998), the studied littoral zone forms a homogeneous coastal sector that does not receive significant sedimentary supplies from rivers or nearshore zones. In fact, sediments supplied by the Gudalquivir River are accumulated on a submerged delta north of the studied area, and the rock shore platforms prevent beach recovery after major storms. Moreover, cliff erosion provides only fine sediments that are unstable on the beach face.

The studied zone is a mesotidal coast with 3.2 m and 1.1 m of spring and neap tidal ranges, respectively. Dominant winds blow from ESE (19.6% of annual occurrence) and WNW (12.8%). Significant wave height is usually lower than 1 m, reaching about 3 m during storms (Reyes et al. 1999). Waves approach the shore from NW and W. As a result, a main northeastward drift is observable between Chipiona and Sanlúcar, and

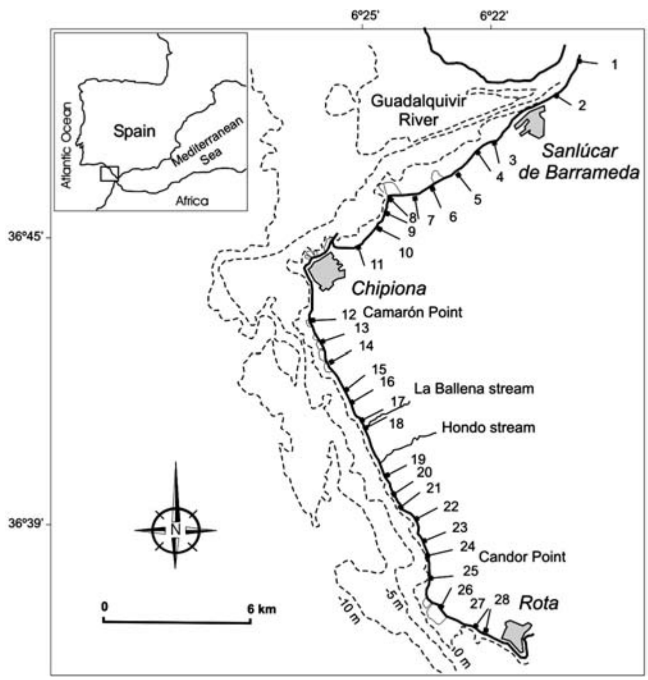

Fig. 1 Location map of the studied zone. The 28-indexed, shore-normal lines mark the transects along which measurements were taken

a southeastward littoral drift prevails in the Chipiona-Rota sector.

Following Rodríguez et al. (2003), in the eastern Gulf of Cadiz, winter storms mainly occur during December and January and, secondary, in February–March and their generation is related to the NAO (North Atlantic Oscillation) climate variable, which is associated with differences in atmospheric pressures at sea level between Azores and Iceland. In Southern Europe, positive NAO values are related to low cyclonic activity and vice versa (Rodwell et al. 1999).

In the studied littoral, the lack of a coastal management policy brought about great urban chaos. The most important municipalities, Sanlúcar de Barrameda, Chipiona and Rota, experienced a considerable population growth during the last decade, and nowadays have a total amount of 110,000 inhabitants, a number that is doubled during summer time. Main land uses are represented by tourism (summer houses and hotels), traditional and intensive agricultural and fishing activities, and industry. Most of these activities or human constructions are nowadays threatened or damaged by erosion processes (Fig. 2), and have been constructed within the ‘‘protection’’ and ‘‘influence’’ zones defined by the law (Spanish Coastal Act, 1988). Within the former, which extends 100 m landward, any kind of construction is prohibited, and within the latter, which extends 500 m landward, only a low-density building construction is allowed.

Methods

The present work is based on the interpretation of seven series of aerial photographs collected in 1956, 1977, 1984, 1989, 1992, 1994 and 2001 at scales ranging from 1/33,000 to 1/5,000.

By this procedure, main morphological features were identified and verified by qualitative and quantitative field observations, i.e. measurement of dune and cliff heights, degree of dune vegetation cover, etc.

Reconstruction of coastline evolution was based on measurements taken at 28 transects homogeneously spaced along the littoral (Fig. 1). The transects were drawn along rectilinear lines normal to the shoreline and passing through reference points such as road intersections, corners of buildings and other human structures identified in all used aerial photos. Distances between the reference points and the coastline were measured along each transect, being the coastline generally identified with the cliff top or the toe of vegetated dunes in order to avoid problems related to sea level position because of tidal and atmospheric variations (Dolan et al. 1980; Moore 2000; Pajak and Leatherman 2002). Erosion and accumulation rates were calculated according to the ‘‘end point rate’’ methodology (Dolan et al. 1991; Jiménez and Sánchez-Arcilla 1993).

In order to solve photo inaccuracy, control measures made in aerial photos were compared with surveys carried out in the analytic topographic map of Andalusia,

Fig. 2 **a** Escarpment in dune ridges close to Point Candor, **b** cliff erosion at La Ballena beach, **c** rip-rap revetment constructed to protect a summer house at Peginas and **d** collapsed parking area at Punta Candor due to erosion processes

at 1/10,000 scale (Instituto Cartográfico de Anadalucía 2000). By this procedure, the inaccuracy of each photogrammetric flight and its arithmetic average value were calculated. In a further step, the percentage of inaccuracy (e%) for a certain flight was applied to the erosion/accretion measures surveyed along each one of the 28 transects (Domínguez et al. 2004). Such surveyed distances were referred to the 1956 surveys that were considered as "zero distance" along all transects:

$$d = D - D_{1956} \quad (1)$$

$$+i = d + (D \times e\%) \quad (2)$$

$$-i = d - (D \times e\%) \quad (3)$$

where d is the distance referred to the 1956 survey, D is the distance measured on the photo, D_{1956} the distance surveyed in the photograph of 1956 and $+i$ and $-i$ the upper and lower range of error, in meters.

In order to express retreat or accumulation rates in m/year, it is important to calculate inaccuracy for each transect in the two flights that limit a time range: maximum and minimum errors (by excess, +iM, and by default, −im) were taken into account and typified according to the resulting accretion/retreat rate:

$$A = \mathrm{DM} + (+\mathrm{iM}) \quad (4)$$

$$B = \mathrm{Dm} - (-\mathrm{im}) \quad (5)$$

$$E = [(A - B)/I] - T \quad (6)$$

where DM is the greatest distance and Dm is the smallest, I the amplitude range in years, T the considered retreat/accretion rate (in m/year), and E the inaccuracy expressed in meters of erosion/accretion per year for the considered rate. Finally, estimated values of littoral evolution were divided into five types ranging from strong erosion to strong accretion (Fig. 3).

In order to assess land uses in the coastal zone, data from several different sources were compiled: oblique and vertical aerial photos (scale 1:5,000) respectively taken in 2001 and 2002 by the "Demarcación de Costas" Service (Spanish Ministry of Environment), the Land Use Map of the Junta de Andalusia (Junta de Andalusia, 2000) and the Agenda 21 Environmental Project (Diputación Provincial de Cádiz 2003). All this information was complemented by accurate field observations on the characteristics of human activities and land uses, like the degree and type of coastal occupation. As a further step, land uses were grouped into four different types ranging from capital land use to recreational and naturalistic uses. Finally, such information was related to littoral evolution trends in order to obtain a final map of coastal vulnerability to erosion.

Results and discussion

The main results, concerning coastal evolution rates and relationships between coastal landforms and land uses are presented in Figs. 3 and 4.

Coastal morphology

Dunes, usually 2- to 3-m-high, are present at Points Espiritu Santo, Montijo and Camarón and in the sector between Point Candor and Rota, where they are fixed by a well-developed pinewood cover (Fig. 4). North of Point Candor, high dunes appear (10–12 m), covered by a thin vegetation cover. Well developed cliffs along the littoral reach the maximum elevation of 10 m at Point Montijo. Heights of 3–4 m are observed south of Point Camarón and decrease gradually southward, until Point Candor, where the cliffs are finally overlaid by a dune field. Rock shore platforms are smooth and wide:

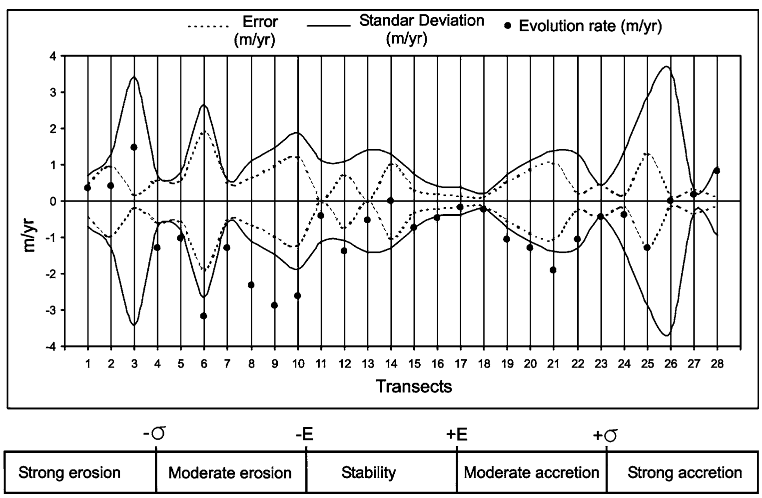

Fig. 3 Erosion/accretion rates at the 28 transects for the period 1956–2001. Errors (E) associated with the measurements carried out at each transect are represented by the *dashed line*. Standard deviation (σ) of the estimated rates is represented by the *continuous line*

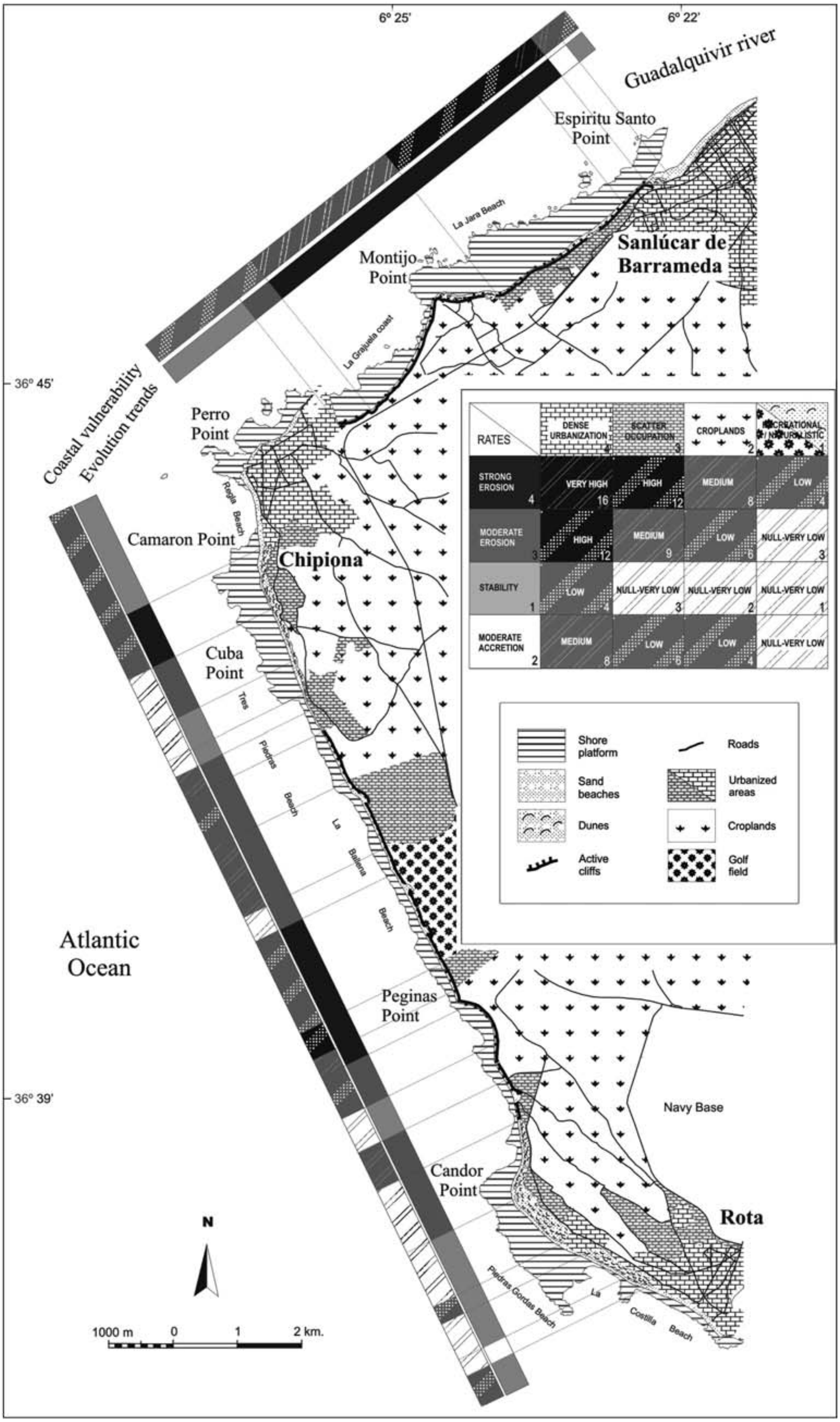

Fig. 4 Morphological features, erosion rates, land uses and coastal vulnerability of the studied littoral

maximum widths (500 m) are observed at Points Montijo, Camarón and Candor (Fig. 4). All these natural features are severely affected by erosion processes that produce periodical dune escarpment and cliff retreat during winter time (Fig. 2c, d).

Coastal evolution rates

Different values of erosion and accretion were observed along the studied littoral for the period 1956–2001. In order to make the results comparable in a qualitative and objective way, it was necessary to determine different types of erosion/accretion rates. For this purpose, two parameters were used (Fig. 3): (1) the calculated error of the accumulation rate for the entire studied period (1956–2001) and (2) the standard deviation of the accretion/retreat rates calculated at each transect for the seven studied photogrammetric flights. In order to eliminate subjectivity linked to the type of measured points (dune toe or cliff top), errors were used to determine zones of stability (when the measured rate falls within the error range—dashed line in Fig. 3), and standard deviation was used to determine the different erosion/accretion rates (continuous line in Fig. 3). In fact, the evolution rate of these different points presents a certain subjectivity strictly linked to the dynamics of the measured points: a dune toe can record accretion or erosion, but cliffs can only record erosion.

In the light of these results, five types of coastal changes were obtained (Fig. 3): strong and moderate erosion, stable, moderate and strong accretion. No point recorded major accretion in the studied littoral (Fig. 4). The greatest erosion was recorded in the northern coastal sector, between Sanlúcar and Chipiona, and also at Peginas. High erosion rates on the Sanlúcar-Chipiona sector are linked to easily erodible cliffs, because in this zone they are composed of sands and silts, and to the orientation of the coastline, which makes it highly exposed to storms arriving from the NW.

Stability was recorded only at the small dunes at Point Espiritu Santo and Piedras Gordas beach (Fig. 4). A certain accretion in Espiritu Santo may be related to the sediments supplied by the Gudalquivir River and especially to the action of NE winds that redistribute sands previously accumulated by the northeastward littoral drift. At Piedras Gordas, accretion is related to its sheltered location and to the local prevalence of northwestward littoral currents, which interact with the submerged platform promoting accumulation during low-tide conditions (Anfuso and Gracia 2005).

Land uses and structures

As in many other coastal areas, in the studied littoral erosion processes have locally been prevented by protection works, concentrated on very specific sites to solve local and urgent problems, i.e. they were undertaken under remedial rather than preventive conditions, without a general erosion management plan. Main coastal defence works in the studied zone consist of riprap revetments, composed of rock blocks placed at a cliff toe to protect summer houses or recreational infrastructures threatened by imminent collapse (Fig. 2).

Furthermore, small groins (at Chipiona and Rota) and a submerged breakwater (at Chipiona), were constructed to prevent longshore and cross-shore sand transport, in order to improve beach stability after nourishment works (Muñoz and Gutiérrez 1999; Anfuso et al. 2001).

Human activities developed along the littoral were mapped and divided into several land-use types: (1) "dense urbanization" zones are related to the main villages, (2) "scatter occupation" zones include low urbanized areas, essentially summer houses and farms, (3) "croplands" include zones devoted to traditional agricultural uses, and (4) "recreational and naturalistic" zones include the dune ridges close to Point Candor, stabilized by a pinewood and used for recreational activities, and a golf camp close to La Ballena beach (Fig. 4).

Coastal vulnerability

The vulnerability to erosion indicates the susceptibility of a beach segment to experience damage: coastal erosion constitutes a risk not only when it threatens human structures but also when it causes beach erosion, reducing beach capacity for recreation or tourist-use.

In the studied littoral, beaches are quite narrow and their economic value and importance for costal protection is more or less the same along the entire zone. Therefore, the coastal vulnerability types were distinguished based on the combination between the potential cliff/dune retreat or stability (estimated by taking into account the erosion/accretion rates recorded in the 1956–2001 period) and land-use type. Five different types of coastal vulnerability were distinguished: "very high", "high", "medium", "low" and "very low to null" (Fig. 4, Table 1).

Table 1 Distribution of vulnerability types in the studied littoral

Types	Vulnerability					Total
	Very high	High	Medium	Low	Null–very low	
Length (km)	0.5	2.7	5.0	9.3	5.1	22.6
Percentage	2.21	11.94	22.12	41.15	22.56	100

More than one third of the littoral is at risk. Very high vulnerability was only distinguished at Sanlúcar de Barrameda due to the important capital land use in combination with a high retreating rate (1.5 m/year). In general, high and medium vulnerability types were distinguished as a combination of moderate or strong erosion rates and land uses ranging from capital to agricultural (Fig. 4).

The remaining two thirds of the studied coast present low or very low risk. It is the result of high capital uses on stable coastal sectors (Chipiona littoral, protected by hard man-made structures) or low land uses in stable or erosion coastal sections.

The obtained results can be used to identify imminent collapse zones (ICZ). Following Crowell et al. (1999), the ICZ can be defined as the littoral zone extended from the shoreline (in this case considered as cliff top or dune base) landward, with a width equivalent to five times the erosion rate at the site plus 10 ft (about 3 m). At the same time, the future 15-year coastline (hypothetical position of coastal line in the following 15 years) was calculated by taking into account the recorded erosion rate. A 15-year prediction time span was chosen because the predicted coastline position can be calculated for a time span of about one-third of the studied period (Smith and Zarillo 1990; Crowell and others 1991).

The maximum calculated retreat rates are 3 m/year for the northern sector and 1.5 m/year for the Chipiona–Rota sector. In the former, the ICZ and the 15-yr coastline are projected, respectively, 15 and 45 m landward from the considered shoreline; in the second sector they are located, respectively, 8.5 and 22.5 m landward from the shoreline. Many human constructions lie within the ICZ, especially between Point Espiritu Santo and Point Montijo, and at Tres Piedras and Piedras Gordas beaches. In addition, the 15-year predicted coastline includes the recently urbanized zones landward of La Ballena beach.

Implications for coastal erosion management

Most protective rip-rap revetments in the zone have triggered erosion at both sides of the structures. Probably, the best solution for these local erosion problems would be the abandonment or relocation of single structures, mostly summer houses, threatened by coastal erosion and the protection of high density urban areas. The rip-rap revetment technique used for coastal defence seems to be not very effective and rather nourishment projects—accompanied by the construction of small engineering structures—could be planned to solve existing erosion problems, always keeping in mind that a healthy beach is the best form of coastal defence. Furthermore, a wide beach would have an important recreational benefit, especially at Sanlúcar village and La Ballena, which is a tourist village constructed in the last 5 years on a rapidly eroding coastal sector where the cliff is protected by a narrow dry beach, not very attractive for tourists.

Finally, sand for nourishment purposes can be dredged from the nearshore zone or at the entrances of the existing ports that need periodic maintenance. Some quantities of sand can also be gathered from accreting beaches, where sand is landward-transported by wind (i.e. in the vicinity of Point Espiritu Santo and in Piedras Gordas) and lost from the coastal sedimentary budget.

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