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Monitoring morphological changes along the coast of Huelva (SW Spain) using soft-copy photogrammetry and GIS

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Abstract. This contribution deals with the use of different sources of data (field surveys with total station and GPS, air photographs and topographic maps) as well as their integrated digital treatment in a GIS context to quantify the morphological changes in a ridge of coastal dunes in the southwest of Spain. The results show very high and incrementing rates of foredune retreat, significant losses of foredune surface and a clear negative sedimentary balance (lowering and inland migration) in its recent evolution (1979-1996). Two processes can explain this evolution: (1) marine erosion and (2) the re-activation of aeolian deflation. The combined use of GPS (code/phase) and soft-copy photogrammetry seem to provide the best for monitoring future changes.

Keywords: Air photograph; Andalusia; Dune ridge; Morphodynamics.

Abbreviations: DTM = Digital Terrain Model; GPS = Global Positioning System.

Introduction to the study area

The study area chosen to test the methodology is the stretch of coastal dune ridges between the settlements of Isla Cristina and La Antilla in the west of the province of Huelva (SW Spain), close to the Portuguese border (Figs. 1-3). The zone investigated in detail, ca. 700 m. long and to the west of La Antilla, was chosen for several reasons:

1. It is very dynamic, because it is under the hydrodynamic impact of the Atlantic Ocean. The coast is mesotidal, i.e. it is exposed to wave forces of low to medium energy (76% of the waves are less than 50 cm high), predominantly from the southwest; the mean tidal range is 2.10 m (Borrego et al. 1992). The combination of wave force and direction of approach with the alignment of the coast produces a strong dominant littoral drift which moves sediments eastward. The net eastward movement has recently been modelled mathematically at 260 000 m^3/yr (Medina 1991).

2. The continuous belt of coastal dunes seen today is the result of the recent evolution from a system of barrier islands which was still active in the 19th century. Since the 19th century the tidal inlets separating the barrier islands have been closing to form littoral spits associated with the outlets of the principal rivers (Guadiana, Piedras, Carreras). Nonetheless, between the river outlets we find a ridge of dunes which shelters old lagoons now infilled and converted into salt marshes beyond which, inland, is the former cliff-line marking the line of maximum postglacial transgression (ca. 6000 BP). Over and above the ecological value of any coastal dune system and the important role they play in maintaining the morphodynamic equilibrium of beaches, in this case they also serve as a natural dyke protecting the areas behind from inundation, as they are below the mean level of high spring tides (tidal marshes) and in part are drained and dried out for various human activities.

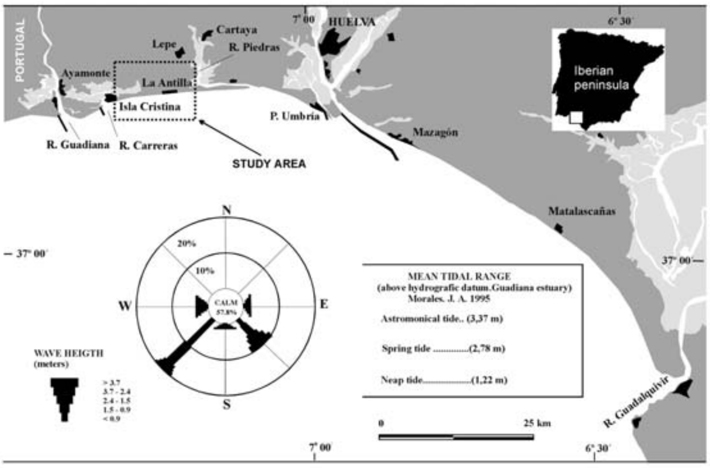

Fig. 1. The study area.

3. These dune systems have been considered as economically marginal areas, the only activity being fishing centred at Isla Cristina with the rest unoccupied and in places, as in the study area, being zones of reforestation. However, since the 1960s, there has been a two way intensification of human pressure:
(1) an increased fishing activity at Isla Cristina and the problems of maintaining a fixed frontier with Portugal in the late 1970s led to the construction of a system of jetties at the outlets of the Guadiana and Carreras which have had a major impact on long-shore sediment transfer; (2) the development of tourist resort facilities has passed through two phases: a localized development in La Antilla in the 1970s and 1980s, followed in the 1990s by the creation of a major complex at Isla Antilla with associated golf courses and the proliferation of camping sites. For these sites the nearest beach is in the study area and the shortest way is over the dunes.

Recent foredune evolution (1979-1996)

The location of the study site in relation to the aforementioned hydrodynamic of eastward littoral drift and the pressures of tourism, has meant that the processes which have controlled its recent evolution can be summarized into two morphodynamically distinct systems:

1. Marine erosion

Since their construction in the 1970s the jetties have been a total barrier to long-shore sediment transport. The study zone being immediately downstream, has a definite sedimentary deficit and has been subjected to intense marine erosion in which the dunes serve as a sediment reserve. The results are:

(1) the foredunes are subjected to intense erosion processes with significant rates of foredune retreat and the dune face is effectively a cliff;
(2) the marine erosion begins at the western end and moves downdrift;
(3) there is a marked loss of sediment from the foredunes which reduces their role as a sediment reserve in storm events.

2. Aeolian deflation

As can be seen in Fig. 4, the reactivation of deflation processes throughout the dune complex were practically non-existent until the late 1980s. Deflation increased throughout the 1990s linked to the increased tourist presence and, above all, to the uncontrolled access to the beach by campers and other temporary visitors from the nearby tourist facilities and villages. The destruction of sand-fixing vegetation along the different paths across the foredunes has led to the development of blowouts. The morphological effects can be summarized as follows:
(1) inland foredune migration because of blowouts;
(2) general lowering of the fore dune, increasing risk of inundation and the destruction of pine wood in the inner dune complex;
(3) weakening of the dune by the loss of fixing vegetation increases vulnerability to marine erosion.

In general each morphodynamic system contributes to a typical landward migration of the foredunes with significant losses of sediment from this sector of the coastal dynamic system, the destruction of vegetation and an increased risk of inundation.

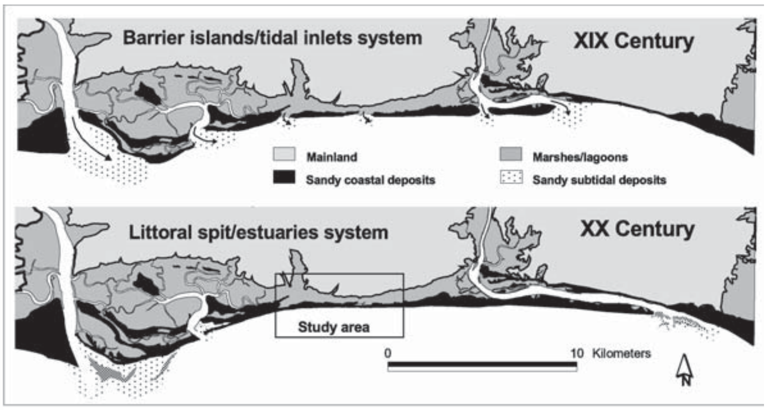

Fig. 2. Area of study: foredune evolutionin south-western Spain (western coast of Huelva.)

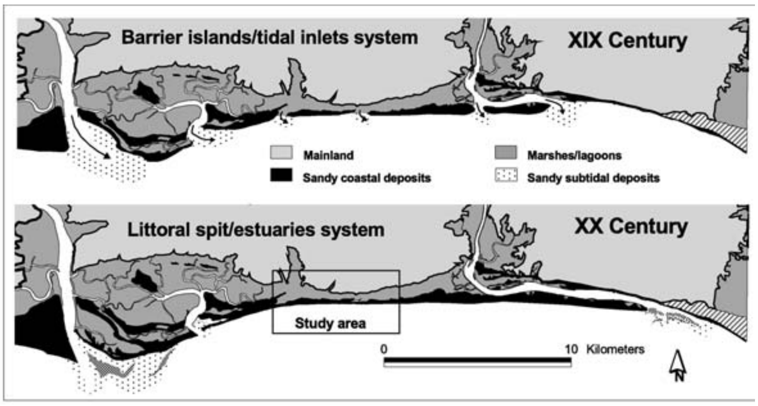

Fig. 3. Detailed area of study; evolution of built-up areas and tourist facilities.

Objectives

To present the results and an evaluation of the sources, techniques and procedures are used to quantify the morphological impact of the aforementioned processes of marine erosion and aeolian deflation at a very detailed scale (1: 1000). The impact can be traced in the following ways:

(1) point measurement of changes in the foredune/backshore line used as a coastline marker in particular locations;
(2) measurement of surface changes in the foredunes either on the seaward face (marine erosion) or on the landward face (inland migration);
(3) temporal changes of foredune volume, DTM construction and evaluation of sediment budget;
(4) spatial changes of volume, relocation, etc. shown by chart differencing analysis i.e. overlay.

Annual rates will be calculated for all these measurements and the result will be presented as maps to facilitate international comparison. Additionally the results will be used to produce animations to allow a fuller understanding of the patterns of change.

Sources and methodology

The diversity of the sources of information used to meet these objectives and the need for integrated data processing makes the use of a GIS virtually essential even though some data require pre- or post-processing before integration into the GIS. For our study area the sources and techniques used were the following.

Cartography

Although cartography at 1 : 1000 is rare in non-urbanized coastal areas, we have found two reference documents with a 1-m contour interval which have provided a planimetric and geometric basis for the GIS (the projection is UTM, the co-ordinates are those for UTM zone 29):

1. A topographic map at 1 : 1000 from the Ministry of Public Works used for the application of the Coastal Law of 1989. The map is based on field survey by classical topographic instrumentation and it was provided in analogue format. The map was digitized and integrated into the GIS for subsequent analysis.

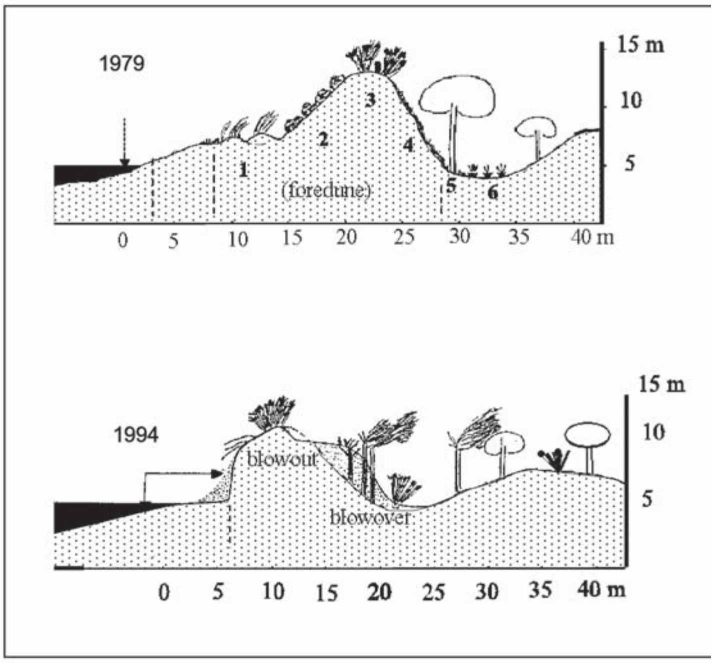

Fig. 4. Processes and effects in foredune evolution (1) marine erosion (sedimentary deficit): coastline retreat; loss of foredune sediments; (2) aeolian deflation: destruction of vegetation due to uncontrolled access to beach through foredune; migration of island due to blowout development; lowering of foredune (risk of flooding).

2. A topographic map 1 : 1000 from the new Andalusian Cartographic Institute produced by stereo-plotting from air photographs and supplied in digital format.

Detailed air photographs

We have available four photogrammetric flights, all in winter, a critical point because of the strong seasonality of the maritime climate in this zone.

February 1979	1 : 10 000
April 1989	1 : 5 000
December 1994	1 : 3 000
February 1996	1 : 3 000

The geometrically consistent integration of the air photos into the GIS required a preliminary digital processing by scanner and Desktop Mapping System 4.0. This software eliminated tilt and radial distortion (Anon. 1996) and allowed the production of vector format output by stereo-plotting (spot height, coastline/foredune planimetry etc.) or raster mosaics (ortho-photos and DTM).

Field survey

The field survey was carried out with a Leica TC600 infrared Total Station with a vertical or horizontal angular accuracy of 5", a distance meter accurate to 3 mm ± 3 ppm and an operating range between 1.1 and 1600 m. This equipment was used to survey the ground control points for air photo rectification and then to assess the actual working accuracy of the Leica 200 GPS system. All GPS surveys were made by a mobile rover receiver (Leica 200 GPS) and post-processed and differentially corrected (Cook et al. 1996) using data from a master receiver (Leica 200 GPS) fixed in a known location (bench mark). The operating range between the two receivers was 10 - 15 km. The three available modes were used as follows:

(1) static mode: x, y, z accuracy = 5 mm ± 1 ppm.: measuring time 10 - 15 min: used for measuring ground control points for new air photos;

(2) stop-and-go mode: x, y, z accuracy = 3 mm ± 1 ppm.: measuring time 15 min to start and 25 s per new point: used to survey point heights on the foredunes in order to improve DTM quality, the coastline using the foredune/backshore contact line, and the 1997 landward limit of foredune propagation;

(3) cinematic mode: x, y accuracy = 3 cm ± 1 ppm and z accuracy = 6 cm ± 1 ppm: measuring time is 15 min to start then automatic continuous measurement: used to survey coastline in 1997.

Results and Interpretation

Annual foredune retreat rate

Each rectified or ortho-photo was introduced into ArcInfo through a compatible format (TIF) and three measurements (west, centre, east) were made at each date. The results are presented in Table 1.

We are clearly dealing with a regressive coast for which all dates show significant rates of retreat that can be explained by the construction of access breakwaters at the ports of Isla Cristina and Ayamonte. There is a progressive increment in the annual rates throughout the period that is consonant with the intensification of human pressure, most notably after 1990. There is also differential net erosion from west to east with high rates in the west especially between 1989 and 1994 when this sector suffered the bulk of the erosion. However, these single annual figures are not necessarily representative and are certainly site dependent, especially given the complex dynamics of the erosion of these beaches over very short time periods – presence of rip currents, giant cusps etc. Nonetheless, since they are used internationally these figures have been included to facilitate comparison with other sites.

Changes in surface area

The backshore/foredune line was interpreted and digitized from the rectified photographs or ortho-photos for each date. An overlay process was carried out for each pair of dates and the results were overlaid on the ortho-photos before printing. See Table 2. As can be seen in Fig. 5 and Table 2, the spatial continuity of aerial photography produces results that are more detailed and interesting to interpret:

1. During the first period (1979-1989) all change was by marine erosion of the seaward side of the foredunes, as they, and especially their landward side, were well controlled by vegetation. Human pressure was very low in this period and concentrated in the built-up areas of La Antilla and Isla Cristina.

2. In the second period (1989-1994), foredune retreat rate actually doubled but was spatially concentrated in the western sector. Yet, because of the higher incidence of tourist pressure and the opening of the first camping sites, the vegetation is beginning to be destroyed by dune paths and landward dune migration begins although it is as yet only 1/6 of the seaward face's retreat rate.

3. During the third period (1994-1996), rates of retreat on the seaward side were up to 6 × those of the first period, even though in this case the spread of marine erosion was more homogeneous. The rates of foredune landward migration continued at similar rates despite having a reduced width of dune to draw on for material.

Table 1. Retreat of the foredune along the Huelva coast.

	West	Centre	East
1979 - 19 89	15.0 m (1.5 m/yr)	10.0 m (1.0 m/yr)	6.0 m (0.6 m/yr)
1989 - 1994	20.5 m (4.5 m/yr)	7.5 m (1.6 m/yr)	3.5 m (0.7 m/yr)
1994 - 1996	10.0 m[1] (5.0 m/yr)	12.0 m (6.0 m/yr)	12.0 m (6.0 m /yr)

[1]The rates of retreat have been calculated by dividing by 2. In reality December 1994 - February 1996 requires division by 1.18 giving yearly rates of 8.4, 10.2, and 10.2 m/yr respectively.

In summary the three-phase evolution of coastal erosion in this zone is:

1979-1989: well-developed foredunes, with two ridges, and fixed by vegetation, developed into a seaward eroded foredune with a landward slope still controlled by vegetation. This evolution is explained by sediment deficit caused by the combined impact of jetties and dam-regulated river discharges. Human pressure is scant.

1989-1994: expansion of built-up areas and the evolution of camp sites intensified human pressure, especially through cross-dune paths to the beach. The sedimentary deficit continued to increase. At the same time the dunes were weakened by vegetation loss and lowered by deflation which together produced landward-moving blow-outs.

1994-1996: the sediment deficit continued to increase for the same reasons as before and human pressure became still stronger, because the number of camp sites increased and so did occasional visits. Blow-outs increased and the heavy storms in the winter of 1995 caused in some places the foredune to disappear, leaving many of the pines to die subsequently, this from the combined effects of wind, sand, and salt spray.

Table 2. Changes in surface area in the backshore and foredune along the Huelva coast.

	Area lost by retreat	Area gained by inland progression
1979 - 1989	– 6291 m^2 (– 629 m^2 /yr)	0
1989 - 1994	– 5574 m^2 (– 1238 m^2/yr)	+ 1298 m^2 (+ 288 m^2/yr)
1994 - 1996[1]	– 4811 m^2 (– 2405 m^2/yr)	+ 392 m^2 (+ 196 m^2/yr)

As before, the total was divided by 2, but this should have been 1.18, which would have given – 4077 m^2/yr and + 332 m^2/yr.

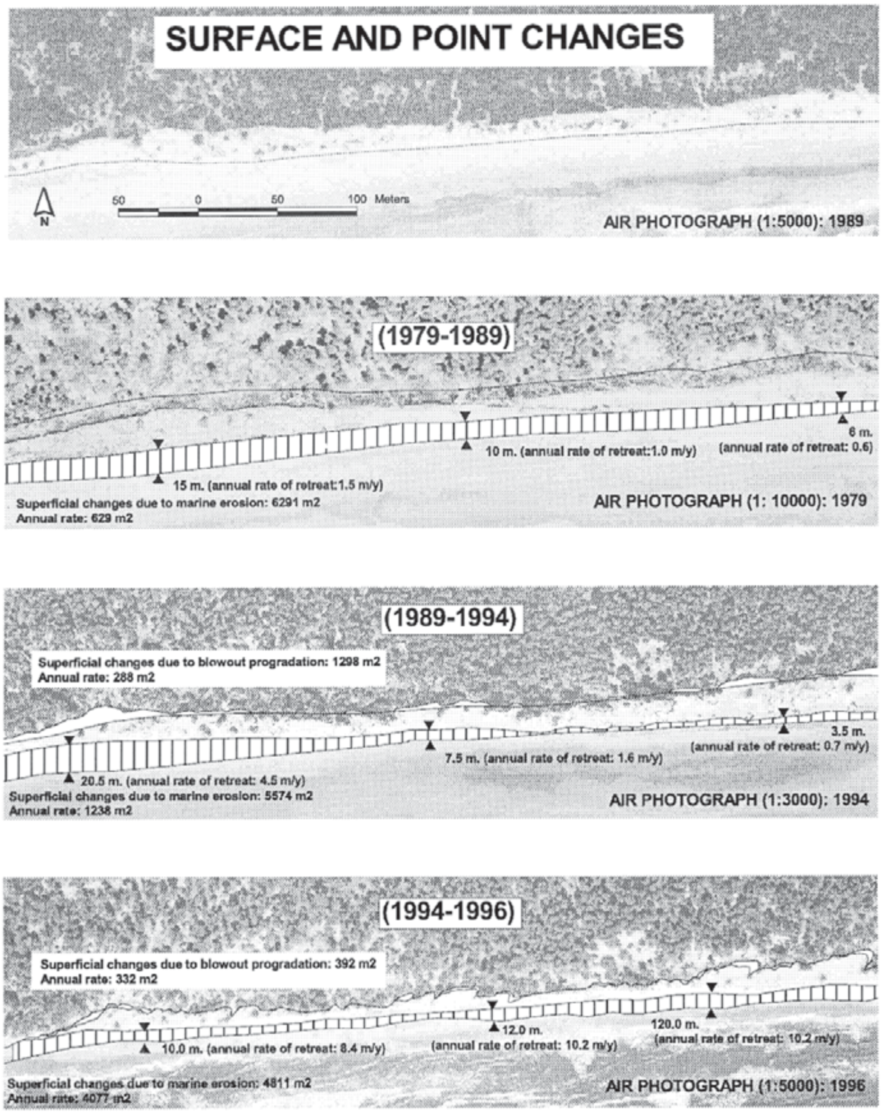

Fig. 5. A series of aerial photographs showing the changes in the dune surface.

Foredune volume calculation and sediment budget

The possibility of obtaining altimetric data from whichever of the sources used has made it possible to characterize these changes in even greater detail. The first stage was to establish how much sediment the foredune had lost or gained, which required the construction of DTMs from the available data. Here we present just the DTMs for 1989 and 1994 (Fig. 6). For these two reference dates the measurements come from the 1 : 1000 topographic map from 1989 with 1-m contour intervals, and from classical field survey and air photos for 1994. Both the contours and the spot heights were digitized and integrated into the GIS. The TIN module of ArcInfo was used to generate the DTM (Brandli 1992) and the GRID module was used to convert to raster and to export as a geo-coded image file for subsequent graphic use. For the other DTMs, and later when we return to the 1989 and 1994 ones, we are using a procedure to integrate the GPS data and an automatic stereo-correlator (Desktop Mapping System 4.0) with pairs of air photos. There are not yet any results from this process.

The foredune volumes calculated were:

for 1989 2 686 094 m^3

for 1994 2 675 713 m^3

This means a change of – 10 381 m^3, an annual rate of – 2077 m^3/yr and an annual rate per m of coastline of 2.6 m^3/yr.

The absolute changes in volume and annual rates of loss reinforce the results calculated from surface area measurements, and indicating the serious loss of material and thus the reduced effectiveness of the dunes as a sediment reserve.

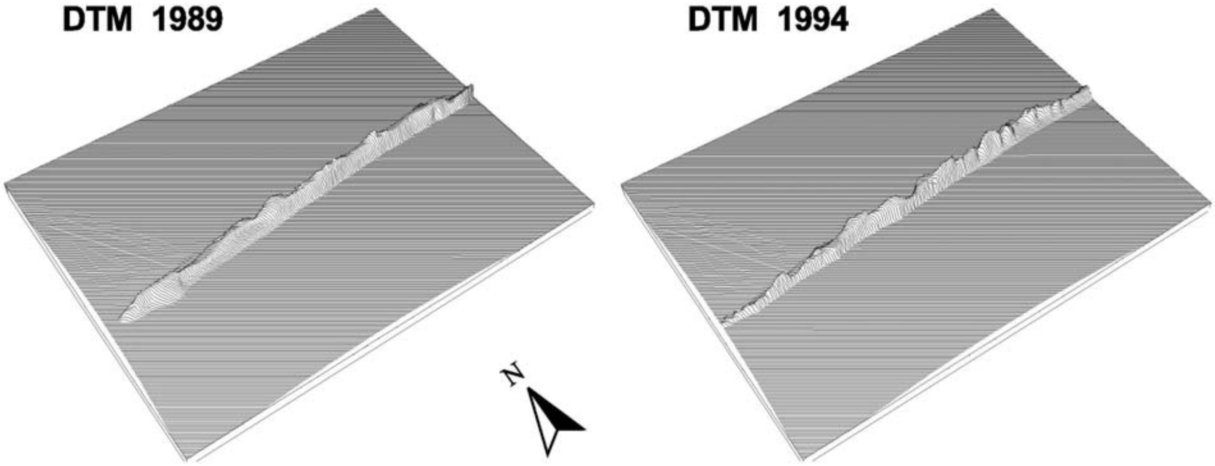

Fig. 6. Digital Terrain Models for the foredunes of the Huelva coast, 1989 and 1994.

Volumetric spatial changes 1989-1994

The DTM does not only allow the quantification of sediment loss but also its location using chart differencing in raster format (overlay). The graphics in Fig. 7 show clearly the four types of sediment redistribution:

1. Areas of foredune lost since 1989 because of marine erosion on the seaward side of the dune. The losses have been calculated at pixel level in these areas and can be seen as dark grey.
2. Areas added to the foredunes since 1989 by inland migration are also quantified at pixel scale and are seen as light grey.
3. Areas of foredune which have lost height by aeolian deflation.
4. Areas of foredune which have gained height by aeolian action.

Fig. 7 shows explicitly the clear predominance of areas with a negative balance, mostly by marine erosion in the western part and seen clearly in the 'cliffing' of the dune in 1994. In the east the loss is associated with deflation caused by tourist activity. In summary all the areas of positive balance are landward.

3D graphic presentation and animation

Using the information from the 1989 and 1994 DTMs, a set of images has been assembled to help understanding dune evolution between these years (Fig. 8). The DTM images were exported to VistaPro 3.0 to make four videos (*.avi) integrated into the GIS via hyperenlace in ArcView 3.0, but playable in any Windows environment. Two of the videos are used to show a flight over

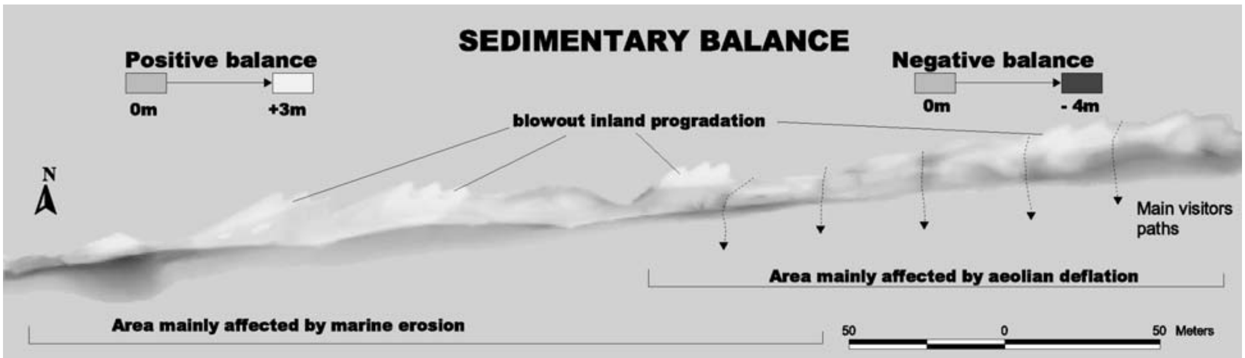

Fig. 7. Sedimentary balance for the foredunes of the Huelva coast.

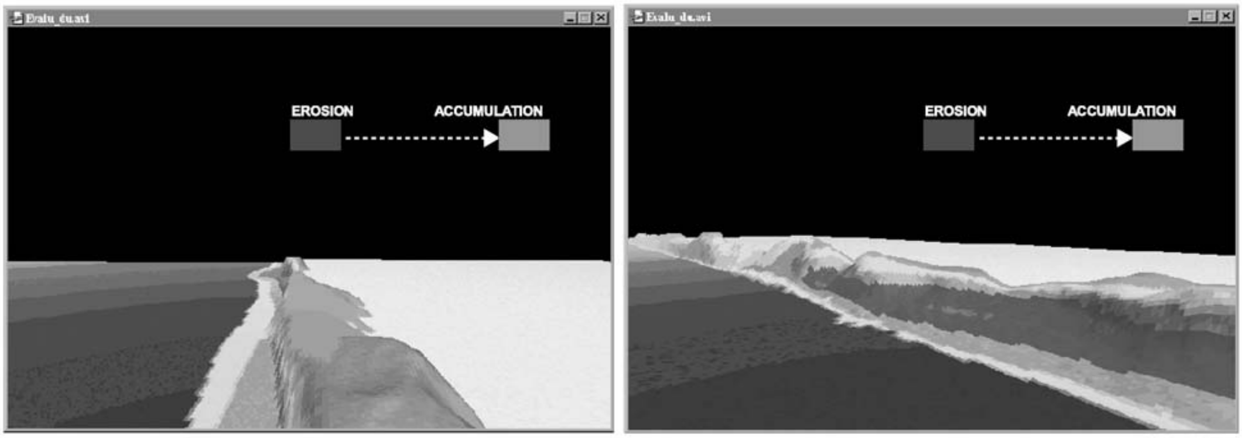

Fig. 8. Screenshot from VistaPro of foredune development along the Huelva coast.

the dune, one for each date but with the view parameters held constant to aid comparison. The third video uses the 1994 DTM with the volumetric changes image overlaid. The fourth is used to model the change from one date to the other making use of the analysis tools from IDRISI to generate the intermediate stages.

Conclusions

The different techniques of analysis all show, very clearly, a foredune undergoing high and increasing erosion, causing the loss of a large amount of sediment from particularly significant areas of dune in a highly popular tourist area. Moreover, the increase in the rate of retreat can be explained in terms of human action, the building of jetties and tourist pressure, especially dune paths which destroy vegetation and lead to blow-outs.

These erosive processes and subsequent deposition lead to spreading of sediment and loss of altitude which eventually will lead to the dune failing to protect the landward zone against salt-water flooding. This has already occurred in some areas. Among all the techniques used to trace the morphological changes in the foredune, the best results seem to come from a combination of high precision GPS (code/phase) and digitized high resolution air photos and soft-copy photogrammetric treatment. The only really effective way to integrate and access the multi-source data is through a GIS but only after the full capability of other specialist software has been applied for specific functions.

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