Geographic Information Systems Applied to Integrated Coastal Zone Management

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Abstract

The littoral is the area where marine and terrestrial processes superpose and interact. Limits of their respective actions are imprecise, as processes which are characteristic of each of these environments do overlap. This particular characteristic makes the littoral zone complex and vulnerable to human activity, which in many cases, causes irretrievable damage to the natural equilibrium. Integrated Coastal Zone Management (ICZM) promotes sustainable coastal development by adapting the use of natural resources in a way that avoids serious damage to the natural environment. This requires an integrated and organized action of all institutions that are involved in coastal development.

Geographic Information Systems (GIS) besides being a useful tool for drawing maps on different scales and projections constitutes an excellent instrument for data analysis and integration due to its ability to identify spatial connections between different information layers. In this way, it is possible to build models for geomorphological evolution and predict changes in the coastal areas.

In order to illustrate this, three examples of GIS applications are presented, which are currently being developed in different areas of the Spanish littoral, coastal hazards, shoreline evolution and coastal sand dune evolution, respectively.

Keywords: Littoral, Coastal Zone Management, Geographic Information Systems (GIS), Sustainable Development.

1. Introduction

Coastal areas have been traditionally the source of wealth for many municipalities that were mainly dedicated to the fishing industry. At the end of the 19th century, tourism in Europe sprung forth, the beach acquiring great relevance as a place for rest and leisure. Since then, the coast has been subjected to an intense exploitation aimed at offering progressively more demanding tourist services. Notwithstanding its value as an important generator of economic, social and landscape resource, it is often forgotten that the coast is a very vulnerable environment, with the highest biological and geological values, that needs strong protective measures in order to be preserved.

In this scenario, the diversity of uses and activities developed in the littoral area makes it necessary to seek the most suitable way to attain compatibility among them and, at the same time, preserve the environment. On the other hand, the threat of climatic change, and the prognoses of a sea-level rise that would flood coastal land, makes it necessary to elaborate coastal development scenarios that take into account all elements. This is the approach undertaken by the ICZM (Integrated Coastal Zone Management), which is trying to define the sustainable management of the littoral. Its implementation is based on two main groups of factors: Firstly, it needs a deep knowledge of the physical environment as well as the relationship between the agents and processes of each one of the fields involved (marine, coastal and terrestrial). Secondly, it needs an appropriate territory management. These factors are, in turn, conditioned by the legal, social and environmental aspects that are established by public, national and local administrations (Rodríguez et al. 2003a; Barragán, 2003). For some years, efforts have been made to implement proper management rules (e.g. CE 13/2002), and methodologies which deal with all the mentioned coastal factors and aspects (Fig. 1). These methodologies come from different institutions (UNESCO, European Commission...), forums and different working groups that suggest policies in order to carry out these tasks in an efficient way (Bondesen, 1996; PNUMA, 1996; Intergovernmental Panel on Climate Change, 1996, 2001, 2007; Olsen et al., 2003; EUROSION, 2004; Coastal Zone Management Program, 2005).

Because of the need to integrate and manage all these factors and aspects related to the coastal zone, GIS appears to be the most appropriate tool to deal with those tasks. This clearly shows the spatial and temporal evolution of dynamic processes as well as the factors that control their behaviour in order to analyze these scenarios better, evaluate the impact on littoral environments and manage them properly (O'Brien et al., 1995; Moe et al., 2000; Li et al., 2000; Zhang and Grassle, 2002; Hamada, 2004). Since GIS was one of the tools recommended in Word Coast Conference in 1993 (Vellinga and Klein, 1993), a number of different projects using GIS applications and methologies for coastal zones have been developed (e.g. BALTICSEAWEB, Laitinen and Neuvonen, 2001; Ocean Biogeographic Information System OBIS, Zhang and Grassle, 2002; Dune Hazard Assessment Tool, NOAA Coastal Services Center, 2003; Coastal Erosion and Shoreland Development Regulation, Miller et al., 2003).

Each coastal zone needs different management strategies and therefore different GIS uses to deal with each problem. Three GIS applications are presented in this paper: 1) In coastal hazards management GIS helps with statistics analysis, needed to carry out a multivariate spatial-temporal model that estimates the probability of hazard occurrence; 2) Dealing with shorelines corresponding to different years, GIS allows the analysis of the evolutionary trends to define the behaviour of the system; 3) GIS used in studies of the evolution of dune fields is essential in order to estimate dune migration rates and analyze all the variables involved in this process.

2. GIS as a coastal management tool

In the littoral zone, GIS is increasingly used as a support tool that allows homogenisation and integration of all the available information into a geodatabase, in order to access data, generate thematic cartography, and perform spatial and geostatistical analysis (Laitinen and Neuvonen, 2001). An amount of relevant information is collected, compiled into the database, converted into more convenient units of information and, finally, introduced into a more formal information system. This characteristic is especially useful, for example, in the integration and analysis of the indices used to identify coastal vulnerability (Doukakis, 2005), offering maps of coastal risk.

The result is a versatile and flexible system. On the one hand the access and use of the data can be achieved through the database model system and on the other hand by using GIS system advantages: editing and data automation, visualization, mapping and map-based tasks, spatial consultation, spatial analysis, and geostatistical analysis. This flexibility allows GIS used in further planning applications in other scenarios (Fig. 2).

In the following sections some GIS applications to coastal management currently developed in different areas of the Mediterranean Spanish littoral are presented.

2.1. *Coastal Hazards GIS application*

Slow but steady degradation of the coastal fringe in much of Europe has gone largely unnoticed until recently, and this will continue and accelerate with sea-level rise, and other coastal hazards. Developing methods to balance protection of people and the economy against the costs of degradation of the coastal environment will require multidisciplinary research. (Nicholls et al., 2007).

A practical example of GIS use in coastal hazards is shown in the problem of rock fall in a cliff sector of the Catalonian Coast (Mediterranean Sea). The main objectives of this study are: physical and mechanical natural environment characterization, stability analysis in the area characterized by previously obtained geo-mechanical parameters, estimate of rock-fall occurrence probability via development of statistical models, elements-at-risk identification, vulnerability analysis, and finally the generation of a landslide risk map.

The coastal waterfront is formed by sandy beaches with smooth slopes and pebbles in some areas. The cliff-surrounded coves are formed by pebbles included in a sand-clay matrix, and covered by a calcareous crust (IGME, 1980). These materials are potentially unstable, and represent a landslide hazard to the beach (Fig. 3). The cliffs are fractured and constitute a potential danger of rocky block-fall onto the beaches where the tourist population is high in the summer.

Streams and gullies transport detrital materials and deposit them onto the beaches as a consequence of heavy rains in the autumn. A detailed hydrological knowledge of the area is needed, because superficial and subterranean waters affect cliff stability by removal of the sedimentary matrix, accelerating the rock fall.

Regarding swell, in this area, during storm and wind events, the short term rise of sea-level caused by meteorological tides could be more than 1m in specific places. The return period for these singular events varies from 10 years (swell height = 1m) to 100 years (swell height = 1,5m) (Sánchez-Arcilla and Jimenez, 1994). Swell action on the cliff in conjunction with the high number of fractures, contributes to the instability of the rocks. Previous works, such as Bray and Hooke (1997), review the possible effects of longer term sea-level rise on soft cliffs. They evaluate different methods of analyzing historical recession rates and provide simple predictive models to estimate cliff sensitivity to predicted sea-level rise.

The considerable amount of information to process requires an organized working methodology. It is therefore, necessary to design and create a graphic and alphanumeric database that integrates all factors that could promote hazardous situations. A thorough and accurate study requires knowledge of the following data: lithology, slope, vegetation, structural conditions, morphological indicators, drainage, climate, fluvial and coastal erosion, seismicity and human action. Elaboration of Digital Elevation Models is useful to obtain topographic variables such as slope, orientation and curvature (Fig. 3). Moreover these models are able to define superficial drainage properties and hydrological basin characteristics. Likewise DEM is an essential tool to get a geomorphological characterization and to identify landslides.

Having collected and organized all these data, it is possible to analyze them and map the potentially unstable areas. Then, it is necessary to determine the elements at risk in the area: population density, natural environment, socioeconomic aspects (infrastructure, economic activities, heritage, etc.) (Ministerio del Interior, 2002). The overlapping of the hazard map and the elements at risk map, allows the evaluation of the vulnerability of the zone. It is important to understand the nature and implications of the threat to and the vulnerability of the population, in order to prevent disasters, minimise the risk and manage the consequences. (Vellinga and Klein, 1993).

GIS helps with statistical analyses, which are needed to carry out a multivariate spatial-temporal model for estimating the rock fall hazard. Given that risk maps are really useful tools to develop strategies to protect the environment and to elaborate a regional plan, a Decision Support System (hereinafter DSS) is implemented to facilitate the extension of this methodology to other coastal areas. This system provides the local administrator with help to elaborate environmental and urban plans.

The database and DSS will provide knowledge of all parameters that have influence on the coast. The knowledge of the sensitive areas and the risk map elaboration helps to manage preventive actions. They allow verification of current land uses and determination of the areas where government legislation will need to be more demanding.

2.2. Shoreline Evolution

One of the main functions of GIS is to allow the comparison of cartographic data previously georeferenced. This powerful characteristic is fundamental for carrying out analysis of coastal changes. The equilibrium of shoreline position depends on environmental conditions and human actions (EUROSION, 2005). If this equilibrium becomes unstable the worst situation will be shoreline retreat. The example presented in this GIS application is the coastal evolution of the Ebro Delta (Fig. 4).

The methodology used to estimate the erosion rates along the coastline is as follows:

1. Acquisition of shoreline position from different dates. These information layers come from several sources: a) digitalization of cartography, b) photogrammetric restitution of aerial photographs, and c) an appropriate digital treatment of satellite images (Rodríguez, 1999). GIS is able to combine the information coming from any of these sources, which allows an extension of the period subject to analysis.
2. Overlapping of shorelines corresponding to different years, in order to obtain erosion and accretion zones. This allows distinguishing between areas where there is a backward movement of coasts and, areas that show contrary behaviour. Then, erosion and accretion areas are calculated. One of the advantages of GIS use in this matter is that the calculation of line lengths**,** area and perimeter of polygons, is immediate.
3. Analysis of the evolutionary trends. It allows defining the behaviour of the system. Whenever the environmental conditions are kept the same, it is possible to make an extrapolation for the future within adequate time margins, allowing anticipation of changes in the zone (Crowell and Buckley, 1993; Rodríguez, 1999).

As a result of the analysis we can conclude that the area which has suffered most erosion is the delta front, especially in the river mouth with a shoreline regression of 1650 m in fifty years; while the spits situated on both extremes of the delta, have undergone major accretion.

The evolutionary trend of the last decade for the Fangar spit gives rise to an analysis of its behaviour, as well as an estimation of the moment at which the closure of the bay may occur. It will occur once the hydrodynamic conditions allow it, modifying the whole system and affecting the economy of the area. This evaluation contributes to the implementation of new preventive policies that avoid or mitigate the effects that this specific phenomenon may cause. The insertion of new data into the GIS allows a dynamic follow-up of coastal processes, which is really important in such variable environments. Since 1999, when Rodríguez carried out the "GIS of the Ebro Delta", several models have been developed to analyze other aspects of the delta dynamics (Ministerio de Medio Ambiente, 2001; Rodríguez et al., 2003b; Sánchez et al., 2005). At present, such a GIS is kept alive and its database represents the starting point of the “Cuantificación y contribución del transporte eólico en los procesos dinámicos y ambientales en el delta del Ebro. Aplicación a su gestión integrada y a la conservación de los ambientes marginales” project. This new project includes the environmental variables derived from shoreline evolution.

*2.3. GIS in Sand Dune Evolution***.**

There are more and more coastal dune system research projects that use GIS as a basic tool (Andrews et al., 2002, Mitasova et al., 2005, Ojeda et al., 2005, Hernández, et al., 2007) in dune evolution studies. The most important GIS task is data integration from different times such as dune perimeter, shoreline position, and spatial analysis using these layers.

For several years now there has been great interest about the effects of sea-level rise on the coast due to the fragility of these systems. The sand-dune field studied is situated in the River Ebro Northern Hemidelta which is affected by erosion problems affecting the dune system. The Ebro Delta is one of the systems vulnerable to sea-level rise because of the low elevation of the deltaic plain. If sea level rises 50 centimetres, half of the Ebro Delta could be under water (Cendrero et al., 2005, IES, 2007). In this case dune systems will be more vulnerable as they will be under wave attack. In order to establish protective actions, it is necessary, on the one hand, to determine and quantify the erosive agents and, on the other hand, to establish an evolution model of the coastal dune system.

The characteristics of the dune ecosystems are affected by the sedimentary dynamics, which in turn are mostly determined by the characteristics of the wind field and sediment properties (Hernández et al., 2002). Therefore, the three main objectives of this work are: the characterization of the physical parameters of the area; determination of aeolian transport rates, and the estimation of the morphodynamic evolution of the coastal dune system.

In this research project, GIS plays an important role because it allows: 1) integration, organization and structuring of the geodata set; 2) DEM generation, necessary to calculate dune volume and therefore to establish the volumetric evolution; 3) estimation of dune migration; 4) determination of dune morphology; 5) dune slope and orientation calculation, 6) creation of possible dune scenarios depending of storm waves, wind strength and sea-level rise. 3D GIS advantages make this technology not only but useful essential in this type of study (Gilman et al., 2001; Marin et al., 2005; Sánchez et al., 2005).

Different data types related to wind transport, swell, sediments and vegetation (e.g. wind speed and direction, topography, bathymetry, aeolian landscape, soil humidity) are integrated into the geodatabase. These data are necessary to calculate aeolian transport and at the same time the dune field evolution. Thus, coastal sand dunes of the Ebro Delta are sedimentologically, geomorphologically, meteorologically and oceanographically characterized.

Dune evolution is determined on two different time scales: short-term and long-term. GPS-D (Global Position Systems Differential) is used in the study of short-term dune evolution. Field surveys in the Ebro Delta have been carried out monthly over the course of a year with GPS-D. This technology speeds up data acquisition and allows obtaining accurate positioning data.

These requirements make GPS-D a suitable technology for coastal dune systems. More than 23,000 (x, y, z) points were acquired and processed to generate the DEM, improving the sand volume calculation (Fig. 5). In this way, the seasonal dynamics of the dune field as well as wind transport are estimated. Aerial photographs from different years, between 1927 and 2004, were georeferenced and then digitalized in order to obtain the sand dune field boundary for each year. The long-term dune evolution in 2D is established from the overlapping of the resulting layers. Long-term volumetric evolution of the dune field is estimated from the DEM, derived from processing aerial photograph with photogrammetric software.

Another source used increasingly to acquire topographic data is LIDAR (Light Detection and Ranging) technology, which allows obtaining terrain information more efficiently. It is a laser scanner installed in an aircraft in the same way as a photogrammetric camera. Laser pulses are emitted towards the ground with high repetition rates per second and are reflected back to the instrument (Brovelli et al., 2002). LIDAR data have to be processed to get surface altimetry (DEM). This technology achieves at least one metre planimetric and fifteen centimetres altimetric precision.

The main GIS advantages are the following: dune shape recognition, growth velocity, dune mobility, volume calculation, vector and raster DEM generation and net aeolian transport rates.

3. Conclusions

ICZM is increasingly integrated in local, national and international administrations. Implementation of those management policies needs a tool able to store and display all information related to the target area as well as to carry out spatial, visual and statistical analysis into the information layers. Mapping and GIS are tools clearly focused on territorial management and planning. Specifically, GIS is presented as an interesting instrument to integrate territorial data, making tasks such as variable analysis easier, its inclusion in a predictive model, and future scene simulations.

However GIS implementation has been a slow process, and although a few administrations still use traditional land management methods, most of them are using GIS as their main management tool. Conventional cartography, due to its low flexibility and limited characteristics, was not able to consider all the elements involved in the management of marine and coastal resources.

There are many cases in which GIS is useful in land management. It is an excellent tool in the development of disaster emergency plans. Regarding coastal hazard management, GIS allows potentially hazardous areas to be identified and preventive policies to be established in order to avoid serious damage. Likewise GIS is an essential tool in environmental behaviour studies (evolutionary trend analysis and system characterization) needed to manage the coastal system properly.

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7. Figure legends, tables, figures, schemes

Figure captions

Figure 1. Flow diagram showing the integration of all aspects and factors having influence on the problem of coastal management.

Figure 2. Example of cartographic document generated with GIS for coastal management. Maps, aerial photographs, statistics, tables, and graphs that allow establishing the environmental conditions and their spatial distributions.

Figure 3. Coastal cliffs in south-Tarragona (Catalonian Coast, Spain). Left: Blocks have fallen over the cove as a consequence of coastal erosion in cliff areas. Right: generation of cliff Digital Elevation Model created with topographic data obtained from Total Station. Data are structured in a vector model (Triangulated Irregular Network-TIN) with illumination from NW.

Figure 4. Main rates of erosion (mouth) and accretion (both spits) observed in Ebro Delta from 1957 to 1998.

Figure 5. Left: Location of dune field at Fangar Spit. Right: Digital Elevation Model of the area obtained from Differential GPS data in one of the field surveys carried out during 2005.

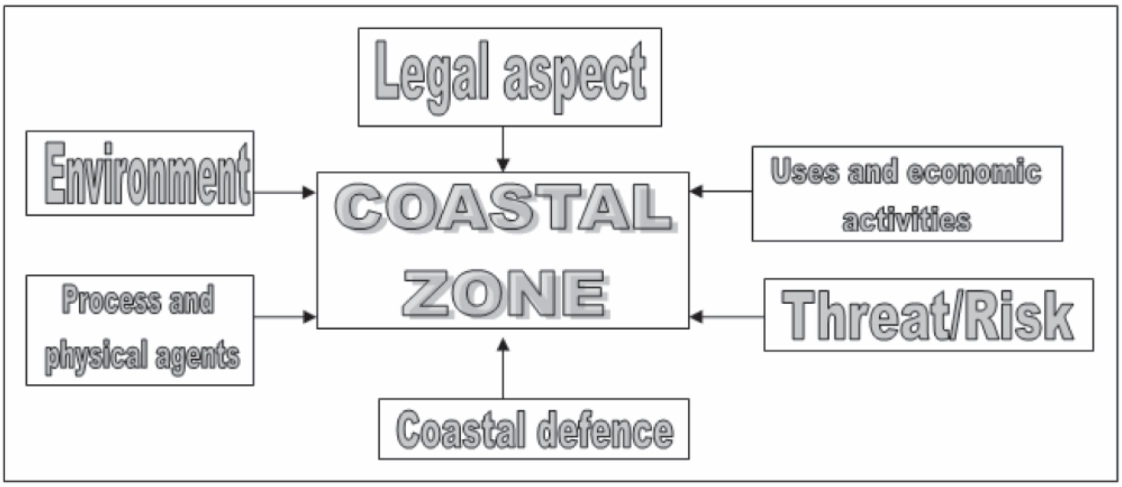
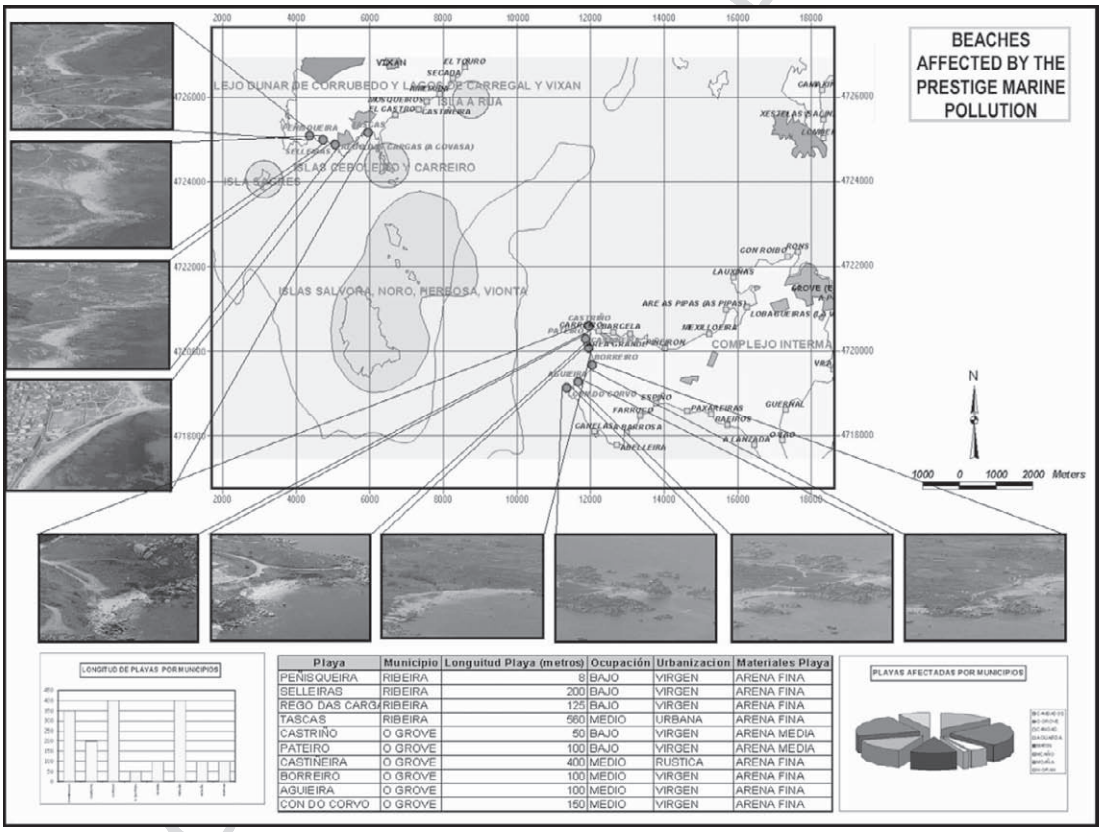

Legal aspect
Environment
COASTAL
ZONE
Uses and economic activities
Process and physical agents
Threat/Risk
Coastal defence

Figure 1



Playa	Municipio	Longuitud Playa (metros)	Ocupación	Urbanizacion	Materiales Playa
PEÑISQUEIRA	RIBEIRA	8	BAJO	VIRGEN	ARENA FINA
SELLEIRAS	RIBEIRA	200	BAJO	VIRGEN	ARENA FINA
REGO DAS CARGA	RIBEIRA	125	BAJO	VIRGEN	ARENA FINA
TASCAS	RIBEIRA	560	MEDIO	URBANA	ARENA FINA
CASTRIÑO	O GROVE	50	BAJO	VIRGEN	ARENA MEDIA
PATEIRO	O GROVE	100	BAJO	VIRGEN	ARENA MEDIA
CASTIÑEIRA	O GROVE	400	MEDIO	RUSTICA	ARENA FINA
BORREIRO	O GROVE	100	MEDIO	VIRGEN	ARENA FINA
AGUIEIRA	O GROVE	100	MEDIO	VIRGEN	ARENA FINA
CON DO CORVO	O GROVE	150	MEDIO	VIRGEN	ARENA FINA

Figure 2

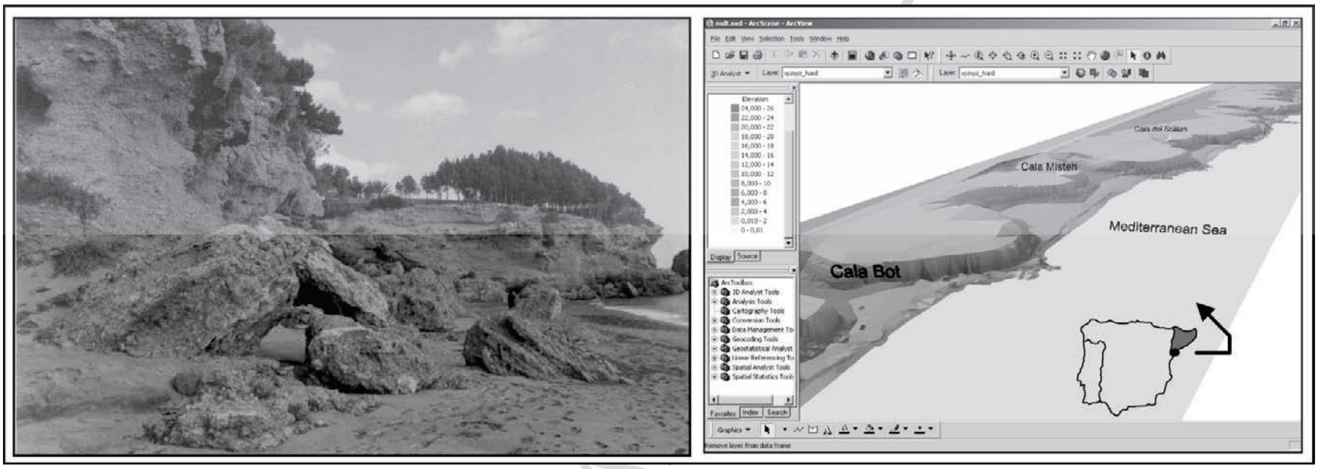

Cala Bot
Cala Misteri
Cala del Solsum
Mediterranean Sea
ArcScene - ArcView
Elevation

Figure 3

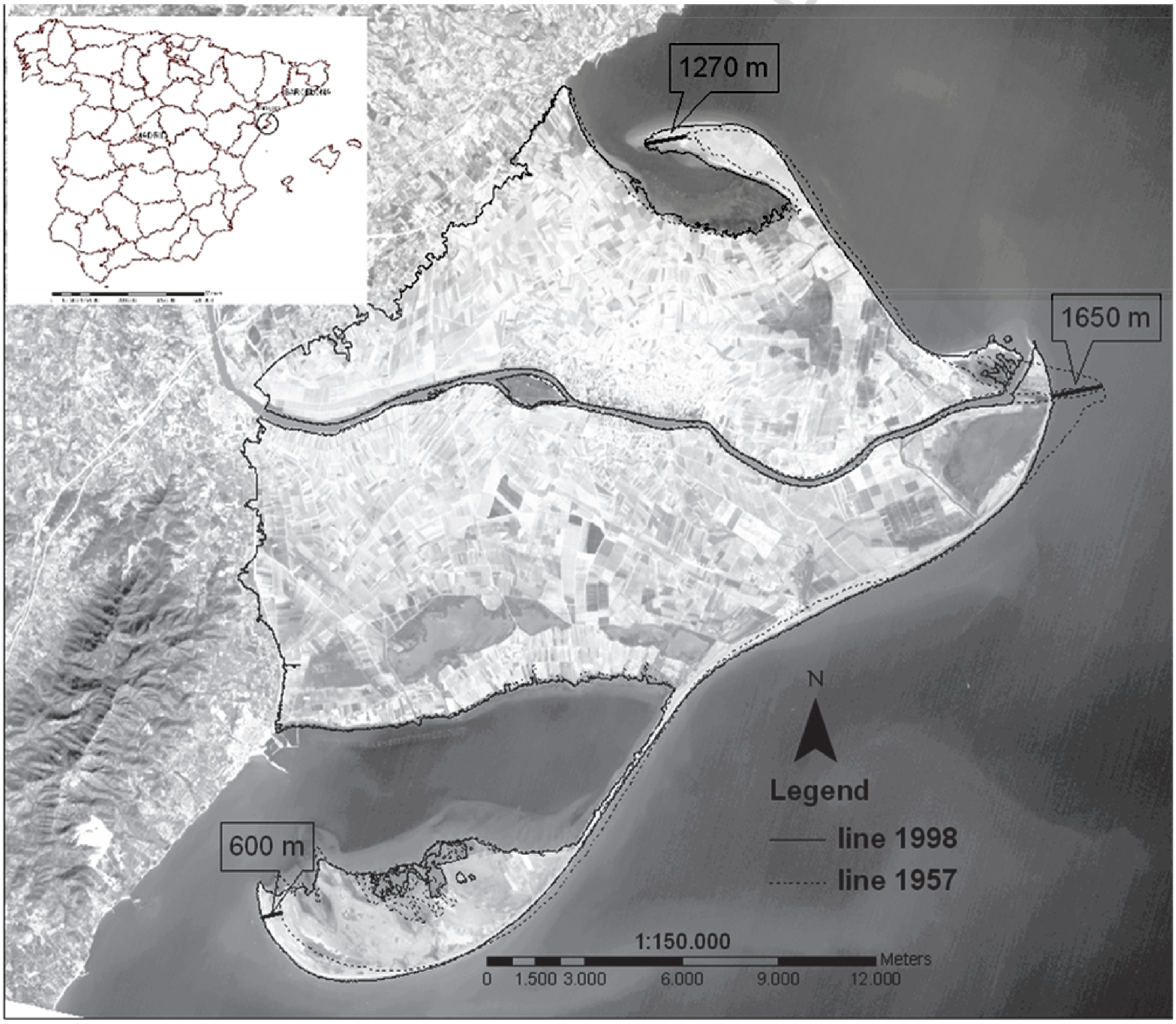

1270 m
1650 m
600 m
Legend
line 1998
line 1957
1:150.000
0 1.500 3.000 6.000 9.000 12.000
Meters
N

Figure 4

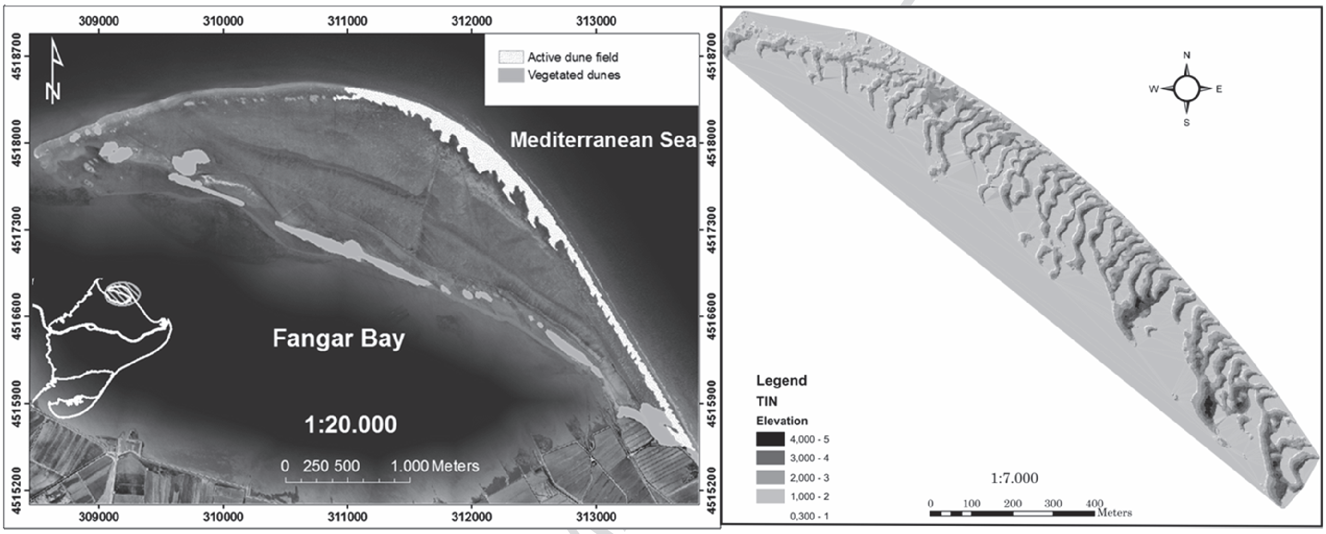

309000
310000
311000
312000
313000
4518700
4518000
4517300
4516600
4515900
4515200
Active dune field
Vegetated dunes
Mediterranean Sea
Fangar Bay
1:20.000
0 250 500 1.000 Meters
N
W
E
S
Legend
TIN
Elevation
4,000 - 5
3,000 - 4
2,000 - 3
1,000 - 2
0,300 - 1
1:7.000
0 100 200 300 400 Meters

Figure 5