

Application of Geographical Information Systems on Portuguese Coastal Projects

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ABSTRACT

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The Portuguese northwest coastal zone is included in one of the most critical European coastal zones and presents serious coastal problems in almost all its extension. Various incidents have occurred in this area, such as coastal erosion, flooding, destruction of infrastructures and sea defences, dune ruptures, and overtopping. High urban, economic and tourist pressures also occur in this area. Erosion problems and the coastline retreat are related to the reduction of the sources of sedimentary deposition, generally as a consequence of total or partial regularization of rivers, construction of harbour breakwaters, and dredging works. It is important to have monitoring procedures to observe the coastline evolution that could be a quantifiable qualitative indicator of the vulnerability and risk of those coastal areas, especially in some areas where it is necessary to build defence structures to protect coastal settlements. In this context the Geographic Information Systems (GIS) play an important role, as they permit the integration, storing, manipulation and analysis of different kinds and formats of data. In this paper four GIS applications will be presented. They were carried out on the Portuguese west coast and related to the design of coastal defence structures and to the evolution of the coastline.

ADDITIONAL INDEX WORDS: *GIS, coastal protection, coastal defences, management.*

INTRODUCTION

The coastal zone changes constantly, as a result of actions of the winds, waves, tides, mean sea level variation, climatic changes, variations provoked by human action and other factors that especially affect the transport of sediment. The erosion or the accretion are the visible result of coastline processes and they reveal its evolution and dynamic character (DONOVAN *et al.*, 2002).

Considering the various and complex problems that occur in the coastal zone it is necessary to use tools capable of updating different kinds of existing information/data, of analyzing, of building different scenarios/options and of producing diagrams and layouts that technical staff, civil society and politicians could understand. In this context, the Geographical Information Systems (GIS) have a great potential. The main objective of this work is to present the potentialities of this tool, namely for the project and design of coastal defence structures, for displaying coastline evolution, for storing and manipulation of the available data, as well as its updating in a systematic way.

As we have said, various applications have been developed using GIS tools and will be presented in this paper. These applications are the following:

- Aguda detached breakwater design;
- Coastline evolution between Espinho and Ovar municipalities;
- Retreated artificial sand dune in the Centre Region;
- Costa da Caparica groins field rehabilitation and artificial sand nourishment.

The software used in these applications was the ArcView 3.1, the ArcInfo 7.2.1 and the AutoCad Land Desktop 3.

With these developed applications, it is intended to show the great utility of GIS in coastal defence design. It is capable of presenting various scenarios, helping in management and decision making and monitoring its evolution. The use of GIS has been shown to be very helpful because it was necessary to overlay various kinds of data, and very useful in spatial analysis. In this way it enables researchers to draw conclusions that will support decisions.

The four applications described are located on the west coast of Portugal (Figure 1) where high sea waves occur (more than 10 m).

The first application is located on Aguda beach (10 km south of Porto), the second one between Espinho and Ovar municipalities, the third one in the municipalities of Ílhavo, Vagos and Mira (the southern sand spit of Aveiro lagoon). The last one is located on the south side of the Tagus river inlet in Almada municipality (South of Lisbon).

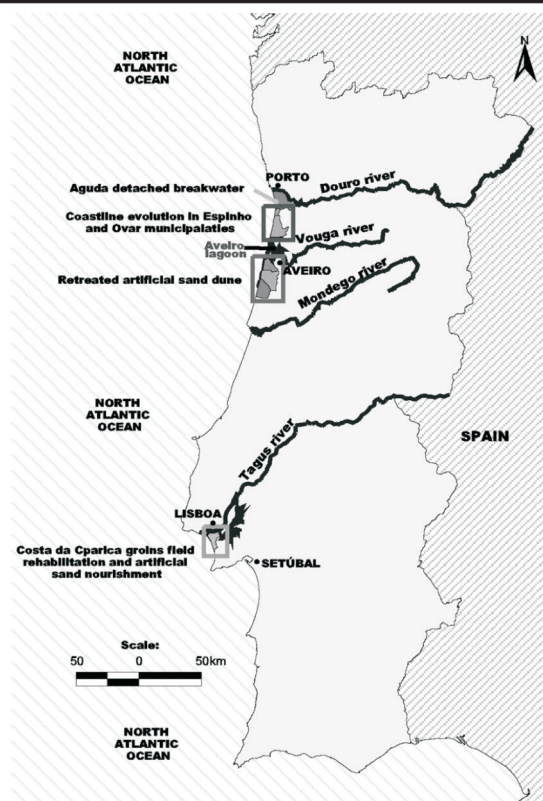


Figure 1. Location of the applications developed.

METHODS

For the development of these applications, a methodology was defined to guarantee that the process is uniform and that there is compatibility and coherence among data. In these applications a great amount of geographical information was used, in different formats (hardcopy, vector, raster), in different Datum (Datum Lisboa and Datum 1973).

After getting the data, an evaluation was made, to define the GIS structure. A hybrid model was selected once in these applications vector and raster data were available.

Scanning

In this process all the information in hardcopy format (military maps 1996 scale 1:25 000, geological maps scale 1:50 000, aerial photographs and a 1972 survey) was converted to raster image. The resolution used was in accordance with the conservation and quality state to ensure that all the information/data stay present on digital format. However, the scanning of maps and aerial photographs could introduce sources of error affecting the subsequent use of these data.

Geo-referencing

The information in raster format was geo-referenced in accordance with the military coordinates (Gauss Projection, International Ellipsoid, Lisboa Datum). To realize such a process ArcInfo 7.2.1 was used, based on common points and coordinates presented in the maps. The maps that were already in digital format, but with different coordinates systems, were converted on-line in a tool of the Portuguese Army Geographical Institute (www.igeoe.pt).

Vectorization

This process was realized to convert some raster information to vector information such as, municipality boundaries, coastline evolution, geological data and other information essential to the applications. This task was done using Arc View 3.1.

Conversion

In this task the vector data in AutoCad format (dxf and dwg) was converted to ArcInfo 7.2.1 coverages and after to shapefiles format.

Digital Data Treatment

The information that results from conversion processes were joining, clips, and merges in several shapefiles and coverages. This task was realized using the ArcView 3.1 (GeoProcessing Wizard), and ArcInfo 7.2.1.

Clean, Creation of Topologies and ID Codes

After the vectorization process and the digital data treatment, the data resulting was submitted to a quality control and a validation process. In this way the error resulting especially from the vectorization, such as duplication of lines, overshoots, undershoots and others were detected and consequently deleted or corrected. The clean topologies process was done with the ArcInfo 7.2.1. The ID's codes were attributed to each geographical element using the ArcView 3.1.

Spatial Analysis

Several analyses were made for the four applications. Most of them are common to all case studies, but some of them are specific to each application.

Land Use and Geological Maps

In all applications the land use was analyzed, determining the areas and percentage. It was possible to observe the type of land use present in the areas adjacent to the interventions.

The geological map was considered only for the second

application (coastline evolution between Espinho and Ovar municipalities) with the purpose of getting areas to be analyzed in Microsoft Excel. It was also possible to make a qualitative analysis to verify the relationship between the geological formation and the urban occupation.

Digital Terrain Models

In the four applications, 3D models for the structures designed for terrain and for the urban settlements (first and second applications) were made, using a Triangular Irregular Network (TIN). These models were important to verify the influence of urban areas, especially in the second case, as well as to observe the sand dune cliff of the second and third applications. It was also important for the visualization of the implantation coastal structures and their spatial relationship with the urban areas where they will be constructed.

These models were converted into grids and used on the elaboration of cross and longitudinal sections of the coastal zone and structures, as well as to determine the line of interception between the terrain and the structure.

Profile Elaboration

The profiles were made with two different methods. The first one was recurring to the Spatial Tools that permit the collection of point series of the grids to dbf files. Afterwards graphics with these groups of points were analyzed and created. The second one was using the Profile and Profile Extractor 6.0, extensions of the ArcView that permit one to obtain the graphic profile directly on ArcView or export the values to other applications such as Microsoft Excel. The Profile Extractor also allows the observation of submerged and non-submerged areas.

Determination of Interception Lines

This analysis was made in all applications except the second one. Using the extension LIDAR data handler, and its grid subtraction function, it was possible to determine the line of interception between land and the structure very easily. This line results from the values equal to zero presented on the grid, resulting from the subtraction between the grids of structure and terrain.

Determination of Volumes

To determine the volumes of the structural components, on the detached breakwater, the retreated artificial sand dune and on the Costa da Caparica groins field, the grid resulting from the subtraction in TIN was converted.

Determination of Retreat and Accretion Areas

This analysis was made in the second application between different coastlines (1973/1975 and 1996) and scales. With this analysis it was possible to monitor the areas where the erosion occurs and its intensity. The determination of the erosion and accretion rates was made on the basis of stretches with similar coastline behaviour. After calculating the areas of these stretches, their linear length was measured. In this way their total retreat was calculated and divided by the temporal period (23 years), which provided the mean rate of erosion and accretion per year.

RESULTS AND ANALYSIS

Aguda Detached Breakwater

The detached breakwater was a coastal structure demanded by the Aguda fisherman since 1936. The objective of the structure is the protection of the village and assuring the safety of the fishermen when the waves are strongest. But only in 1999, with the Coastal Zone Management Plan (POOC) approval, was the previous study and the defence structure design realized and then constructed (2001-2002).

To realize these tasks, ArcView 3.1 and ArcInfo 7.2.1 were used.



Figure 2. Several options overlay and detached breakwater 3D model (final solution).

Using GIS was possible, in the first phase of the study, to overlap and compare several options, the solution proposed by the fishermen and the final solution (Figure 2). The fishermen's option was considered based on buoys placed on the sea. The coordinates of the buoys were recorded and imported to the ArcView 3.1. With the lines defined by those points and using the buffer tool, the design of the detached breakwater was performed. With the help of the ArcInfo some geometric corrections were made.

A 3D model (TIN) of the structure and of the terrain was made, getting three-dimensional perspective of the beach and of the breakwater (Figure 2). These 3D models were converted into a grid.

Several profiles of the bottom were elaborated, using the resulting data, for the options proposed by the fishermen and for the final solution. The grids were subtracted and with the resulting grid it was possible to determine the line of interception between land and the structure, and visualize areas where it was necessary to use more material for the construction of the defence structure. We also calculated the volumes of rocks and concrete necessary to the construction of a detached breakwater. After the construction those values were compared with the real ones. These volume values were calculated based on TINs resulting from the grids conversion, permitting the determination of volumes on the land side, on the nucleus and on the sea side.

Coastline Evolution between Espinho and Ovar Municipalities

The coastal zone between Espinho and Cape Mondego is one of the most problematic areas in terms of erosion, on the Portuguese coast. The erosion is very evident, the following factors contributing to this phenomenon: the high exposure to the sea action, the sandy characteristics, the decreasing amounts

of sediment, the strong waves and currents and human action.

The erosion problem it is not recent, news of such phenomena being known since the second half of the XIX century, with a medium coastal retreat of 8 m/year.

In this stretch there are five important urban settlements: Espinho, Paramos, Esmoriz, Cortegaça e Furadouro (Figure 3). In the last ten years great urban development has taken place and the population has increased, especially during the summer time. All the settlements are protected by groins and sea walls.

Significant flat lowland areas characterize this coastal stretch, with an orientation NNE-SSW, formed by sandy beaches and sandy dunes with small elevations. Overlapping geological and land use maps, it is possible to verify that urban areas are constructed on soils with high geological vulnerability and with small resistance to the sea action, thus increasing the vulnerability and risk of ecosystems, properties and human populations (Figure 3).

To estimate the evolution of coastline retreat, military maps were used (scale 1:25000) from the years of 1973/1975 and 1996 (hardcopy), and a photogrametric survey of 1996 (scale 1:2000, digital). All the information was manipulated and converted to a compatible format and integrated in a GIS, in accordance with the process already described.

Some analyses, such as the calculation of retreat rates, land use and geological formation areas, the 3D modulation and elaboration of cross section profiles along the coastal area of these municipalities were also carried out.

By analyzing the spatial results, some interesting information was obtained, especially about the coastline retreat indicators and the areas where erosion was more intense during the period of time considered.

According to the geological maps 70% of these municipalities are located on sandy soils. The land use shows that most of the area is occupied by forest (45.9%) and agriculture (23.7%). However, the urban areas are the third important use with 11.9% of the total area.

The sea fronts of the urban areas are near narrow beaches (Figure 3). With the decreasing width of the beaches, the waves will break closer to the sea front, thus increasing the risk of exposure to flooding and coastal defence and other infrastructure destruction.

In this application it was also possible to undertake a quantitative and a qualitative analysis of the coastline retreat for different years (scale 1:25000) - 1996 (scale 1:25000), 1973/1975 (scale 1:25000) - 1996 (scale 1:2000).

It was possible to obtain indicative values of mean erosion rates for these municipalities for the period of 23 years, however with different values for the same sector that could be explain by the different scale of the surveys in analyse. It was possible to verify that almost all the coastal zone has significant retreats.

The exception is the areas located up-drift of the groins, especially on the North groin of Espinho, where accretion of some importance occurs (Figure 3).

In accordance with the cross profiles obtained from the grid in the coastal area, it is possible to observe the destruction and retreat of the dunes, especially between Cortegaça and Furadouro urban settlements. This fact is indicative of the dynamic state that actually occurs in this coastal area.

Table 1. Erosion and accretion rates in the last 23 years.

Sector	1973/1975-1996	1973/1975-1996
	same scale 1:25000	different scale 1:25000-1:2000
1	+2.2 m	+1.8 m
2	-3.3 m	-2.9 m
3	-6.2 m	-5.8 m
4	-3.2 m	-3.2 m
5	-5.9 m	-4.9 m
6	-0.4 m	+0.2 m
7	-5.7 m	-5.1 m
8	-1.0 m	-1.8 m

In Table 1 some values resulting from the comparative analyses between the different coastlines are presented. This area was divided in eight sectors based on the similarity of the retreat behaviour.

It is clearly observed that the sectors with the high values of retreat in both analyses were the sectors 2, 3, 4, 5 and 7.

Retreated Artificial Sand Dune

The implantation area of the retreated artificial sand dune is located in the centre region of Portugal, in Aveiro district, south of Aveiro lagoon inlet, fixed with two breakwaters. This area

has been suffering serious coastline retreats, besides the increase of urban areas and population. This area is a narrow sand spit, formed by sandy dunes with low heights that separate the Aveiro lagoon from the Atlantic Ocean.

In terms of sediment balance, this region is very dependent on the sediment volume from the River Douro and Aveiro lagoon. Before the start of the construction of the big dams on the Douro in 1930, this river guaranteed 90% ($2 \times 10^6 \text{ m}^3/\text{year}$) of the total sediment volume transported to the north Portuguese coast. In present days the River Douro only contributes 13% of the potential solid transport of the natural regime. Associated with

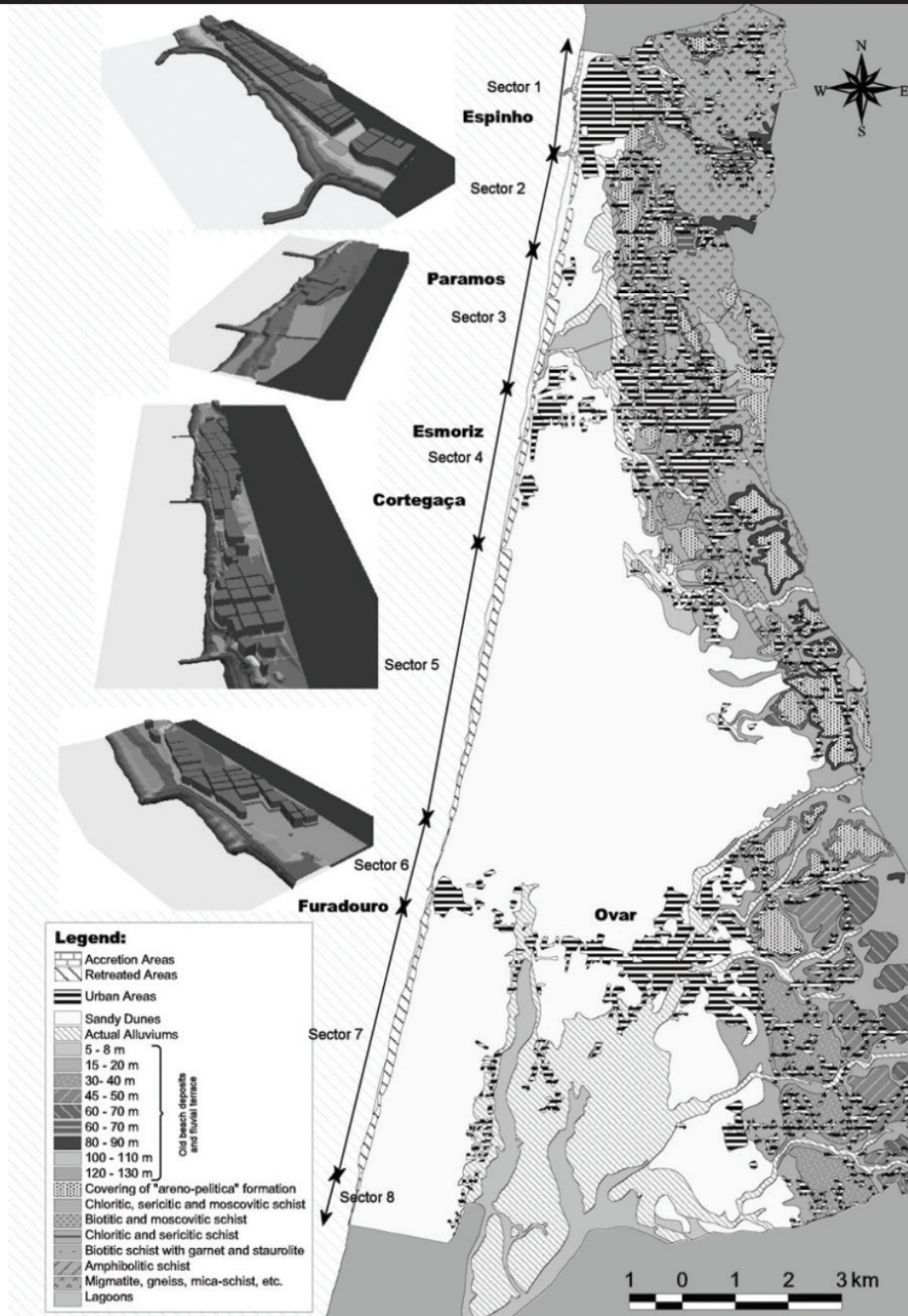


Figure 3. Erosion and accretion location areas, 3D models and geological map with urban areas overlay.

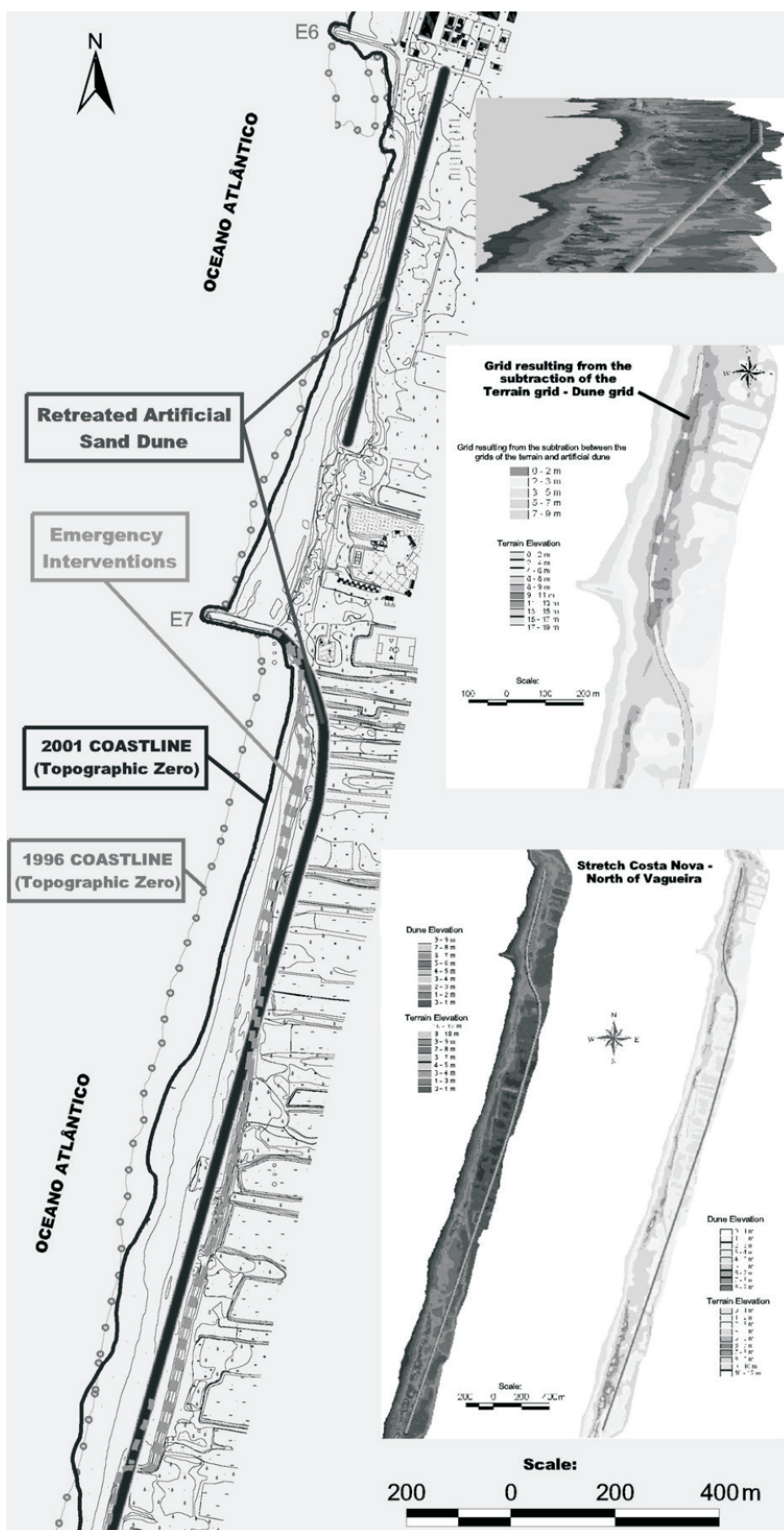


Figure 4. Overlay 1996-2001 survey and 3D models.

this fact, the extraction of sand for construction purposes and the dredging works to maintain the navigation channels in Aveiro harbour also make an important contribution to the reduction of the amount of sediments. Moreover, several defence works (two large breakwaters and at a smaller scale several groins) intercept sediment transit, especially the Aveiro lagoon inlet north breakwater, which results in a high deficit of sediments down-drift.

All the dune extension of the sand spit on the south side of the Aveiro lagoon shows a high risk of rupture to the dune cordon and even to the sand spit. Besides, the great coastline retreat is visible year after year, through reduction in the width of the beaches, dune erosion, overtopping and destruction of dunes, with a high possibility of forming new inlet, (IHRH, 2003).

In the event of new inlets occurring, important and serious changes could occur in aquatic and marine ecosystems, with serious socio-economic consequences. The most significant impacts are the following, (IHRH, 2003):

- Loss of land and salination of agricultural soils;
- Interruption of roads;
- Mira channel salination with important impacts on aquatic communities;
- Direct exposure of lowlands to marine action.

In this area, several defence works were constructed through the 1970s and 80s on the stretch Costa Nova-Vagueira (VELOSO Gomes, F. and Taveira Pinto, F., 1999). In the last few years several ruptures of the sand dunes have occurred, a fact that has led to the construction of emergency works to avoid even more complicated situations.

For these reasons coastal defence interventions, notably the construction of a retreated artificial sand dune and sand beach nourishment, could be important measures, to prevent possible ruptures. This artificial sand dune is considered in the Coastal Management Plan (POOC Ovar-Marinha Grande, 1998) because the existing dune cordon will break. As an alternative to its reconstruction after each new rupture episode, a new retreated artificial sand dune should be built in a place where the process is expected to stabilize. In accordance with the Plan, the retreated artificial sand dune was implemented and designed, using GIS tools.

The 15 km artificial dune will have a +11 m maximum height (hydrographic zero), with a profile width at the crest. This dune is divided into two stretches: the first one corresponds to the artificial sand dune of South Costa Nova-North of Vagueira and the second corresponds to the South of Vagueira-North of Mira. The implantation of the dune was made under a survey from

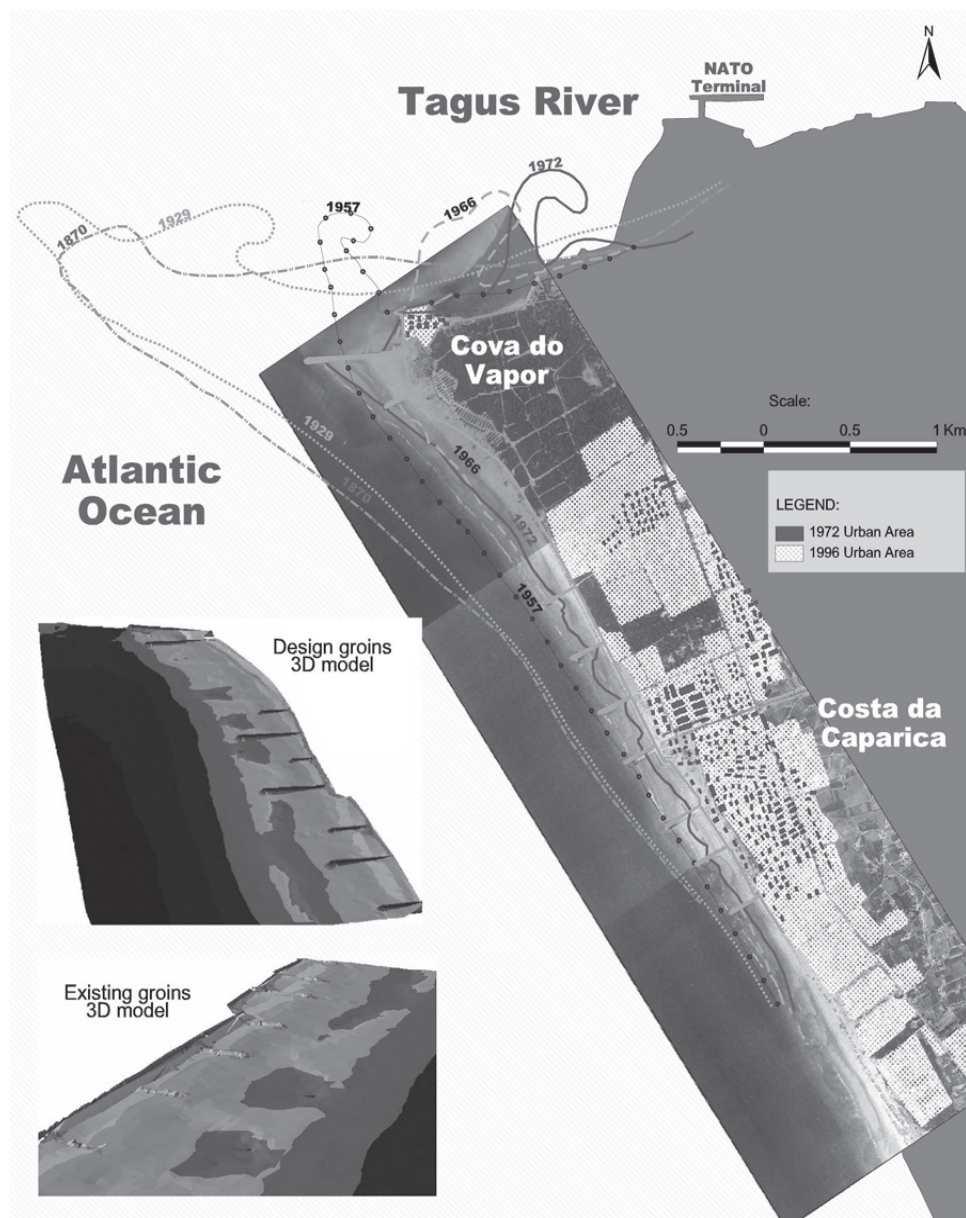


Figure 5. Coastline evolution between 1870 and 1972, 3D models of the existing and designed groins and location of dredging areas.

1996, in dwg format (Autocad), referenced to the topographic zero, since the most recent was not available at that time.

The artificial sand dune design and implementation was realized with the help of the ArcView 3.1 and the ArcInfo 7.2.1 and the extensions spatial analyst, 3D analyst and the LIDAR data handler.

All the information was manipulated and converted to a compatible format and integrated in a GIS, in accordance with the process already described.

Afterwards the central line of the artificial sand dune was designed similar to the alignment predicted on the management plan. Based on this line, several buffers were created and in this way it was possible to define the heights of the various sections of the dune. These buffers were joined in a single coverage, using ArcInfo, and adding to each line the corresponding ID and height. The terrain and the artificial sand dune 3D models were created, and converted into grids (Figure 4). From the grids subtraction, as we have mentioned, the interception line between the structure and the terrain were obtained (Figure 4). It was also possible to verify the exact section and the material needed for the artificial sand dune in each section, as well as the total volume of sediments necessary: approximately 1 000 000 m³ (from off-shore).

By analyzing 3D models of the terrain, it is possible to observe the features of the natural dune: on the first stretch it is fragile with a small width, and in some areas almost non-existent (Figure 4). In the second stretch the natural dune has the same characteristics described above. However after 2.8 km in a southerly direction, the dune grows progressively larger, with width increase but with significant cliffing. By analyzing this model it is also possible to observe lowland areas on the landward side. It is possible to observe that the topographic levels landwards of the dune system decreases, in some places reaching values below 2 m ZT.

It is important to state that this analysis was realized using the 1996 survey. The present situation is more and more critical. After this analysis had almost been concluded, some maps from the 2001 survey were made available. It was only possible compare the 1996 and 2001 coastline alignments, in a region south of Vagueira village. In this overlay it was possible to verify that downdrift a maximum retreat of 80 m occurs (Figure 4). However, between the groins the coastline is more or less stable.

It was also interesting to see that the artificial sand dune, implanted in accordance with the management plan is, in some places already located seawards when it is compared with some emergency interventions. This fact shows that the evaluative line predicted in the management plan was very optimistic (VELOSO GOMES, F. *et al.*, 2002).

In our days the erosion trend is moving to the south, even though there is already in this area an artificial sand dune resulting from the emergency interventions.

Costa da Caparica Groins Field Rehabilitation and Artificial Sand Nourishment

The Cova do Vapor-Costa da Caparica coastline, has, since 1870, suffered important physiographic transformations and coastline retreat, in particular disappearance of the sand spit, which is moving away towards the NATO terminal (Figure 5). This process was reduced with the construction of several defence works, namely the field groin of Costa da Caparica, the three groins in Cova do Vapor and long adherent structures, at the beginning of the 70's.

This area is of a sedimentary type and is dependent on the Tagus River estuary. Especially when storms and flooding occurs, the sediment amount is estimated at between $1,2 \times 10^6$ and 8×10^6 t/year. However, between 1928 and 1986, 65% of the sediments stayed in the system without being released on to the coast, resulting in an intense accumulation on the upper part of the estuary, due to the loss of transport capacity of the fluvial system.

Associated with the erosion problem, this area has important

urban and tourist pressures that provoke some difficulties in the management of the coastal zone.

After the construction of the defence works in 1972, the situation reached a conditional equilibrium state till 2000. No maintenance procedures were made during such a long period. But in the winters of 2001/2002 and 2002/2003 the situation was very critical with the disappearance of large volumes of sand and the erosion of the remaining dune system.

These episodes showed that the rehabilitation of the coastal structures is very important.

This rehabilitation was studied in 2000 with consideration of the physical system and several options were discussed. After evaluating the several proposals a final solution was selected and in 2001 the final study was presented with the selected option. The final solution consists of the rehabilitation and reshaping of the existing defence structures and after that an artificial sand nourishment. In both studies GIS tools were used, ArcView 3.1 and ArcInfo 7.2.1 and AutoCad Land 3 Desktop.

For the first phase of the study, aerial photographs were scanned, as well as the representations of the coastline evolution (Figure 5), that were geo-referenced and rectified with ArcInfo. The coordinate points were obtained from the risk maps from INAG (1999), stretch 5, and military maps 1:25000 from the Army Geographic Institute (IGEOE), M888 series, 1993.

The representation of coastline evolution was digitized as well as the urban area existing at the time. These digitized lines suffer a process of cleaning/correction, to avoid errors resulting from the digitizing process. These lines were converted into a shapefile of points that was exported to Microsoft Excel to build a graphic that could easily show the coastline retreat.

In this graphic it is possible observe that the sand spit between 1870 and 1972 retreated around 3000 m.

For the final solution of this study GIS was also used, which made possible the implantation of structures, the calculation of the interception line between land and the structure, and calculation of different sizes of material volumes needed for the rehabilitation of the groins.

This process was based on a bathymetric survey realized by the Hydrographical Institute, in September 2001, where the final solution was designed, using Autocad Land 3 Desktop, and exported to ArcView 3.1, as a shapefile. The design of groins was made in exactly the same way that was referred to in the artificial sand dune study. Afterwards the structure and the terrain 3D model was created (Figure 5) and immediately transformed into grids to calculate the interception line and material volume. Based on the surveys, the 3D model of the existing coastal defence structures, was also created (Figure 5). It was possible to observe that the groins were very badly damaged, especially at the head. The volume of the existing groins was also calculated and compared with the volumes calculated with the final solution.

Based on the Hydrographical Institute survey, several profiles were made, using the Spatial Tools extension. The profiles were namely:

- Profiles down-drift and up-drift of groins;
- Parallel profiles between groins;
- Bottom profiles down-drift and up-drift of the existing and projected groins.

In accordance with these profiles, the slope is very similar between all groins. However when comparing different areas some variation occurs.

This project also includes artificial beach sand nourishment. The best location of dredging and sand deposit areas were considered and compared. The deposit areas were defined taking into consideration that in future the profiles of the beach will be adjusted by the sea.

The dredging areas were located according to the coordinate points of a geophysical survey realized to characterize the area and to reduce the environmental impacts. These points were given in two coordinate systems, in WGS84 and ED-50, and for this reason were converted to the system used in these applications.

The converted points were located on the maritime map that was scanned, geo-referenced and rectified using the ArcInfo. The points were imported to ArcView 3.1 using the Add Even Theme, and converted afterwards to a shapefile. This location could foresee whether the location is good or not in economic terms as well as the depth and coast distance. In this way, it was possible to make a first analysis to verify the possibility of realizing such intervention and its economic viability.

DISCUSSION

In the first application, the detached breakwater in Aguda beach, the GIS was fundamental for the implantation, calculus of volumes and three dimensional visualization. In this case data from the previous study and from the design process was included, as well as data from it, constituting a database of easy and quick access. In this way it is possible in the future to verify and demonstrate the local influence of this structure in terms of coastal defence, as well as its influence in down-drift and up-drift areas, based on new surveys.

Relative to the second application, it is important to say that using GIS it was possible to compare various coastlines, and thus it was possible to verify rough quantifications that in the last 23 years the dune cordon has moved landward, that widths of beaches have been reduced, and that there have been cross profile changes. It was possible to observe that the coastal defences constructed to reduce the erosion rates or even to increase the beaches accretion and to prevent the flooding and overtopping on the waterfronts in general anticipated the erosion rates down-drift. It was also possible to analyze the land use and the geological formations that are present in the two municipalities under analysis. In this way it was possible to verify that almost all lowland extension is constituted by sand materials with low resistance to the sea action.

In the retreated artificial sand dune case, it is important to say that it is possible to compare different surveys and thus to quantify the volume of sediments that was eroded, to locate areas of height erosion rates and so to locate hot spots in terms of instability, vulnerability and risk of rupture of the natural dune.

The volumes for the artificial dune were calculated and can be up-dated with new surveys due to the high dynamic evolution of the system. The overlapping of the surveys of 1996-2001 showed clearly that the location predicted in management plans was not sufficient. In fact there are already areas where the emergency interventions are placed landwards when compared with the artificial dune.

In the last case, Cova do Vapor - Costa da Caparica, it was possible to verify the enormous retreat of the coastline which occurred between 1870 and 1996. It was possible to calculate the volumes of materials of the existing and projected groins as well several features related to the artificial beach nourishment from off-shore.

CONCLUSIONS

The coastal zone, due to its physical complexity and occupation, needs the knowledge of several variables. To store and join high amounts of data, the best way is to use a GIS. This tool is a great help for projects and design, since it is possible to compare data and temporal evolution, to integrate and manipulate enormous amounts of data. In these applications several difficulties occurred. However with the help of some extensions existing on the internet or with some developed tools it was possible to overcome all the problems that at a first site seem of a very difficult resolution.

Another difficulty was the compatibility of data, especially the coordinate systems since the information was from different sources with different coordinate systems.

With the use of GIS in the coastal studies it is possible to observe the efficiency in terms of defence, and to observe the evolution of erosion in down-drift areas, urban areas expansion and densification, coastline dynamics, profile of the beaches, etc.

As a final remark, the GIS was an important tool in terms of project, design, visualization and evolution, helping the decision maker in the final solution.

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