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The use of a geodatabase to carry out a multivariate analysis of coastline variations at various time and space scales

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ABSTRACT

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This study proposes a method, based on the use of spatial data and aerial photographs to analyse long term evolution of the coastline along the Gâvres – Penthièvre beach system extending over more than 50 km (Southern Brittany; France). Spatial data layers include: air photograph measurements of coastline position through time, sediment cover, coastline morphology and bathymetry. These were combined with current data derived from both field and modelled data to digitise the limits of sediment cells. Aerial photographs analysis also provides data about the location and the density of anthropogenic features established along the coastline through time. All these data were compiled in a personal geodatabase and a series of both spatial and geo-statistical analyses were carried out to assess their spatial relationships. Spatial analyses aim at identifying spatial associations between the type of site evolution *(erosion polygon vs accretion polygon)* and the characteristics of the coastline *(type of sediment cell sites / low density of human pressures / high density of human pressures).* Statistical analyses aim at assessing the statistical dependency between variables defining the spatial associations. The results enable identification of at least two different dynamics controlling coastline movements. At a regional scale coastal dynamics are mainly related to incident wave propagation. Over more local areas, interrelationships between coastal dynamics and increasing concentration of anthropogenic features partly explain coastline variations. Through these results, this study highlights benefits associated with GIS facilities to analyse the role of various factors on coastal dynamics control over a regional scale.

ADDITIONAL INDEX WORDS: *coastline variations, spatial database, spatial analysis*

INTRODUCTION

For the last thirteen years, the use of GIS has been growing in order to cope with numerous tasks dealing with coastal studies such as coastal management (Chapman, 2009, Rodriguez *et al.,* 2009), coastal risk assessments (Brown, 2006, Budetta *et al.,* 2008) or topographic surface evolution (Humphries and Ligdas, 2003; Mills *et al.,* 2005, Dawson and Smithers, 2010). GIS permits the user to represent and analyse complex environmental systems (Pirot and Saint Gérand, 2005) through the use of spatial and statistical analyses and thus enhances the understanding of coastal systems behaviour (Robin and Gourmelon, 2005). Spatial analyses rely on the so-called spatial dependency hypothesis (O'Sullivan and Unwin, 2003) which assumes that the location of a phenomenon is partly linked to the characteristics of its surrounding. However, few studies have addressed the use of spatial analyses supported by a GIS database to explain coastline variations and assess the geomorphological behaviour of coastal systems. Raper *et al.* (2003) and Schupp *et al.* (2005) have undertaken spatial analyses in order to identify the main factors controlling coastline evolutions or sediment dynamics. Prinskin (2003) and Chen *et al.,* (2005) have used spatial databases in order to compare coastline evolutions with land use data. This study aims at exploring the benefits associated with the use of spatial and statistical analysis to explain coastline variations of a sandy beach-dune system located in South Brittany (France). Taking advantage of GIS facilities, the analysis focuses on a set of various factors including both natural and anthropogenic constraints to explain coastline variations over different time intervals and space scales. All these data were stored into a geodatabase. From the geodatabase, spatial distributions of both erosion/accretion areas and controlling factor characteristics were assessed and linked together in order to identify the main factors likely to drive coastline movements.

STUDY AREA

The study area is located in South Brittany and extends along more than 50 km between the Gâvres headland and the Penthièvre isthmus towards the South. It broadly consists of a SW-facing beach-dune system interrupted by the Etel ria (Figure 1). Over the whole beach-dune system, sediment grain size is quite heterogeneous, ranging from medium to coarse sand and pebbly deposits (Estournes *et al.,* 2008). Like most of the southern coast of Brittany, the studied area is mainly subject to westerly and southerly winds. Waves mainly come from northwest and west; their period ranges from 5 to 9 s (Tessier, 2006).

METHOD

The analysis of coastline variation focuses on a set of various factors including both natural and anthropogenic constraints recorded in spatial data layers stored in a spatial database. The organisation and the architecture of the spatial database have been defined through a Conceptual Data Model (CDM) using the Hypergraph Based Data Structure (HBDS) (Pirot and Saint Gérand, 2005). Figure 2 displays the spatial database scheme representing its general structure as well as the relation between the different layers. Using the ArcCatalog- ArcInfo extension of the ArcGis 9.3 package, this spatial database scheme has been implemented into a Geodatabase.

Figure 3 details the different spatial data layers used to elaborate the database as well as interaction processes leading to the creation of new spatial data layers. In a first step, temporal coastline variations were measured from a set of vertical air photographs and ortho-photographs dated from 1952 to 2004. Once the air photographs were geo-rectified, the vegetated front dune line was plotted as a polyline on each photograph. For each couple of dates, the polylines were merged and converted into a polygon layer. Error margins associated with the geo-rectification and coastline digitalisation processes were extracted from each polygon area. These processes lead to the creation of five spatial data layer describing coastline variations (Figure 3).

Next, to characterise the factors controlling coastline variations, sediment transport cells along the coastline were identified from modelled current data derived from the MARS-S4 hydro-numerical and the Inglis & Lacey sediment transport simulation models set up by Safege in 2008. The consistency of the modelling data was assessed with current data from a buoy located 10 km from the studied coastline at a water depth of 12.5m. The sediment transport scheme was then put into relation with a set of spatial data layers recording natural factors likely to interact with sediment transport processes and coastline variations, including data dealing with coastline morphology, orientation, sediment cover and bathymetry. Bathymetry and sediment cover data layer were produced by the Service Hydrographique et Océanographique de la Marine (SHOM) and the Bureau de Recherche Géologique et Minière (BRGM).

Coastal morphology, orientation data layers were digitalised from the 2004 orthophotograph for each straight of the coastline. Four data attributes were created to describe coastline morphology: beach, sand-dune, cliff and saltmarsh. Coastline orientation was digitised at a scale of 1: 2 000. At this scale, five orientations were recognised along the coast: South-East, South, South-West, West and North-West. In a second step, sediment cell boundaries were digitised from the 2004 orthophotograph. Following Carter (1999), three different units were identified along the sediment cell: source sites, transport sites and sink sites. They were identified from visual and screen analysis by overlaying (Figure 3) coastline orientation, morphology, sediment cover, bathymetry and sediment transport data (Carter, 1986; Battiau-Queney, 2003). This analysis permitted the coastline to be divided into different units: (i) source sites located downdrift and associated with coastal morphological features likely to favour sediment delivery such as cliffs (ii) sink sites located updrift and associated with coastal features likely to interrupt sediment transport and favour accumulation, and then (iii) transport areas extending between the two previous site types. According to currents, bathymetry, sediment cover, coastline morphology and orientation, the *Gâvres – Penthièvre* beach dune system can be seen to behave as a vast coastal cell, subdivided into different units, where sediments are transported alongshore from the north towards the southeast by littoral drift. The limits of the different sediment cell units are related to the location of nearshore bedrocks. Intersection processes between coastline variations and sediment cell layers permit to assign to each polygon within sediment cells its orientation (Figure 3).

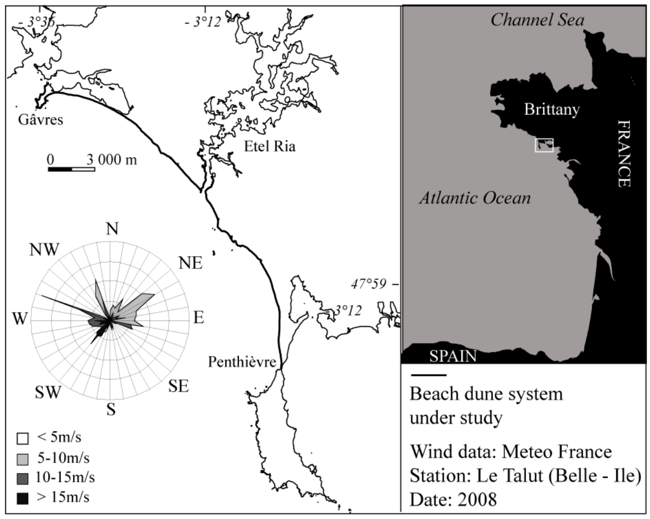


Figure 1: Location map and wind rose

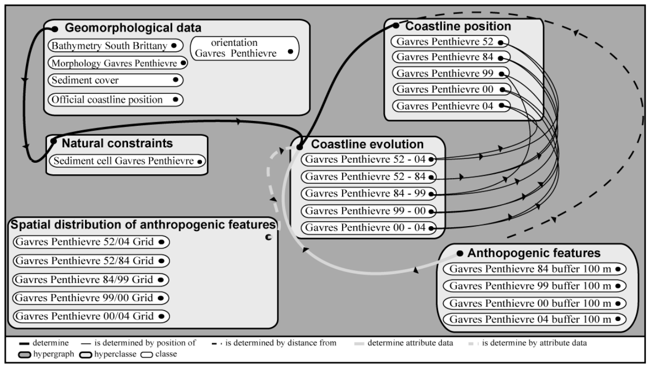


Figure 2: Conceptual scheme of the spatial database

In a third step, attribute data describing anthropogenic features on the coastline during each time interval were added. Anthropogenic feature increase was identified from visual air photographs interpretation. A buffer of 100 m was created around the most recent coastline and any increase of artificial or urban features wes recorded as qualitative attribute data. In the same way, any implementation of coastal pathways was recorded as qualitative attribute data. To assess the spatial distribution of coastline retreat or advance with regard to the location of the different factors stored in the geodatabase, a set of spatial and statistical analyses were carried out. Spatial analysis aims at determining different types of geomorphological behaviour by identifying some spatial associations between the type of site evolution *(erosion polygon vs accretion polygon)* and the natural and anthropogenic characteristics of the coastline *(location within sediment cell / low density of human pressures / high density of human pressures)*. They were conducted over different space scales including the sandy beach-dune system, the sediment cell and more local areas defined by the distribution of anthropogenic features.

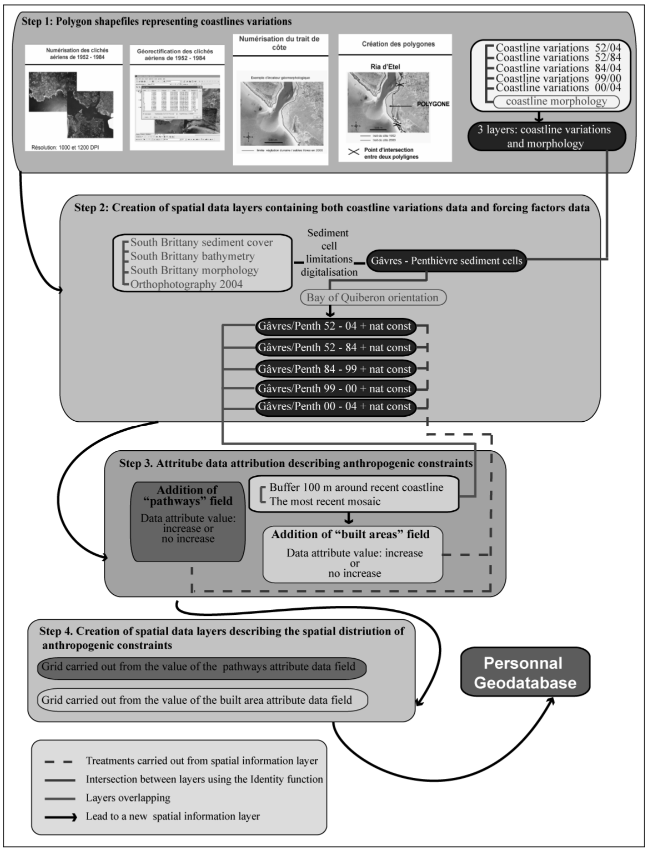


Figure 3: Overlay and intersections processes between spatial data layers

The spatial distribution of the anthropogenic features has been mapped using the ESRI *create vector grid tool* which permits the creation of regular grids from spatial features contained on a spatial data layer source taking into account specific attribute values. Cell sizes have been defined as 500m according to the extent of spatial data layers and contain at least two polygons. Polygon attribute values contained on a cell are assigned to the cell as new attribute data. Selected attribute values are added and the sum is weighted by the polygon areas. These grids permit densities of anthropogenic features to be mapped during each studied time interval. They have been then overlain by the spatial data layers describing the spatial distribution of coastline variations. Statistical analyses aim at assessing the statistical dependency between the variables defining the spatial associations previously discovered. An AMC and a Hierarchical Clustering Analysis have been carried out from data tables extracted from the geodatabase.

RESULTS

Between 1952 and 2004, the beach system has undergone both coastline retreat and advance. In terms of area, 8.04% of the analysed coastline has experienced dune retreat and 91.86% dune advance. This evolution is highly variable but nevertheless several areas still underwent the same evolution over different time intervals. For example, the north of the Gâvres Beach still recorded coastline retreat. During 1952-1984 and 1999-2004, the front dune record severe erosion. On the contrary, during 1984-1999, the beach-dune system underwent a period of dune recovery

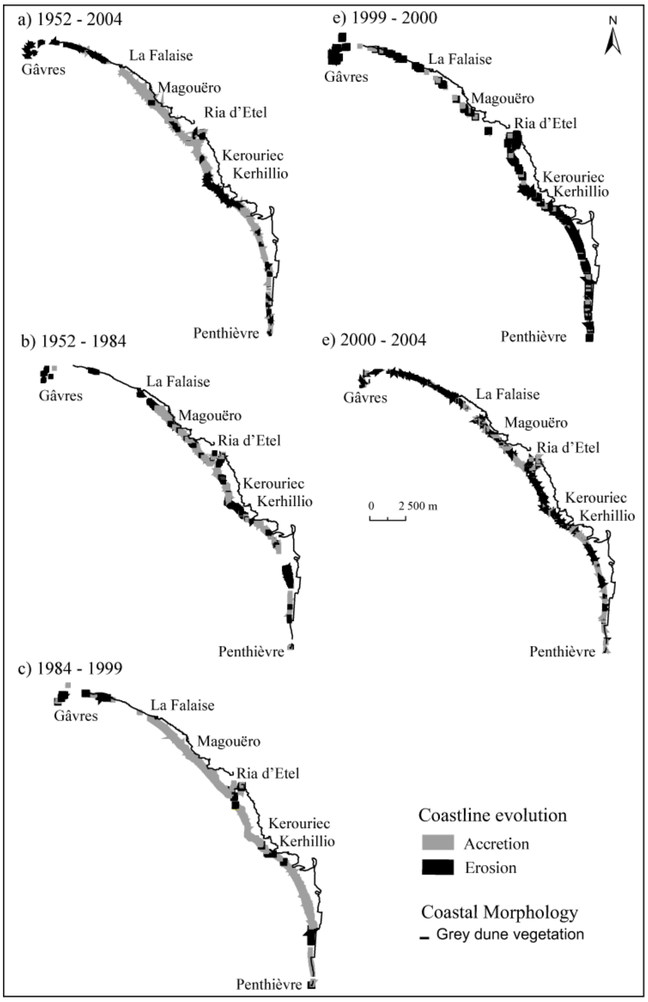
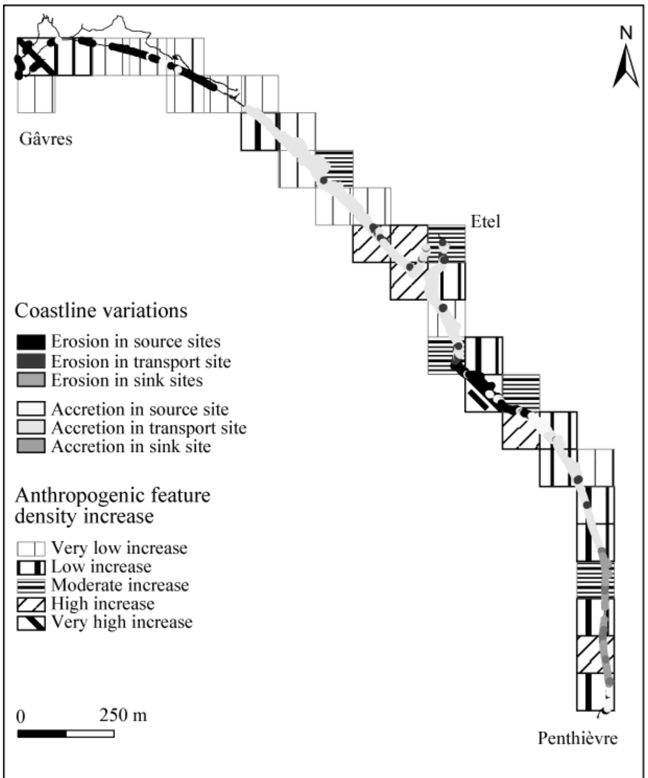


Figure 4: Coastline variations along the Gâvres – Penthièvre beach dune system between 1952 and 2004

with more than 92% of the area in accretion. Both spatial and statistical analyses carried out on a regional scale show that over a regional scale the distribution of erosion and accretion areas match relatively well with these sediment cell delimitations. Figure 5 shows sites undergoing coastline retreat between 1952 and 2004 are more in sites defined as source sites. Inversely, sites undergoing coastline advance are more frequent downdrift, for instance in sites defined as sink sites. Statistical analysis reveals a significant relationship between the "location on the sediment cell" and "coastline variations" variables. Similar results are obtained each time interval under study, suggesting coastline variations are mainly controlled by alongshore wave currents occurring along the sediment cells. Over a more local scale, the distribution of accretion and erosion sites is also dependent on the anthropogenic constraint concentrations. In transport sites and sink sites, coastline retreat occurs where the increase of anthropogenic features established on the coastline is denser (Figure 5). Statistical analyses strengthen these results, by showing most coastline variations are explained by natural factors and minor variations are associated with human factors (Figure 6). Between 1952 and 2004, the first axis obtained from the MCA explains around 44% of the total variance and is defined from variables representing natural factors such as site location along the sediment cell, coastline morphology or orientation and coastline variations. The second axis explains around 16% of the total variance and is defined from a combination of variables representing both natural and anthropogenic factors. Coastline retreat north of the sand dune system at Gâvres is associated with an increase of urban land cover between 1952 and 2004. In the same way, foredune retreat located downdrift in transport and sink areas where retreat should be minor, are associated with an increase of coastal footpaths. The HCA permits the mapping of these changes (Figure 7) and the identification of a number of sites updrift where coastline retreat occurs in association with an increase in number of footpaths.

DISCUSSION

These analyses based upon the use of a spatial database permit the exploration of spatial relationships between the distribution of both natural and anthropogenic features associated with the evolution of the Gâvres – Penthièvre beach-dune system coastline. Results clearly show that over a regional scale, the distribution of both erosion and accretion areas can be related to alongshore currents occurring within the sediment cell. Taking into account the orientation of the coastline to prevailing waves, these results suggest the beaches behave as a vast crenulated bay (Dai, 2004) characterised by a log spiral form and exposed to incident wave energy (Hsu *et al.,* 1987). Over a more local scale, the use of GIS facilities permits to assess the impacts of anthropogenic feature concentrations on coastline variations. At a local level, minor coastline variations could occur independently of coastal currents in relation with anthropogenic pressures exerted on the coast. Such interpretation relies on the acceptation that an increasing number of pathways could impact foredune building and development processes due to an increase of trampling processes (Hylgaard and Liddle, 1981; Nordstrom, 2000). Taking into account all these results, the use of both spatial and geo-statistical analyses lead to the identification of at least too different dynamics driving coastline movements between 1952 and 2004: over a regional scale coastal dynamic are mainly related to incident wave current energy propagation. Over more local areas, interrelationships between coastal dynamics and increasing anthropogenic features concentration does occur and could partly explain coastline variations recorded in transport and sink sites.



	source site	transport site	sink site
Nb of erosion polygon	59	25	9
Nb of accretion polygon	34	55	24
Nb of polygon	93	80	33
% erosion site	63.44%	31.25%	27.27%
% accretion site	36.56%	68.75%	72.73%

Khi² observé= 23.06, Khi² critique= 5.99, ddl= 2, p < 0.0001, a = 0.05

Figure 5: Spatial distribution of erosion and accretion sites between 1952 and 2004 in relation with their position within the sediment cells and anthropogenic feature densities.

CONLCUSION

This study highlights the use of a spatial database to assess the role of various factors likely to control coastline movements. The main interest associated with the use of spatial data and GIS facilities is their ability to address a wide range of data referring to both natural and anthropogenic features over a regional scale. In addition taking advantage of analytical GIS facilities, an accurate assessment of both spatial and statistical relationships between these data permit an assessment of how their interactions could impact the evolution of the coastline over different time and space scales. In the Gâvres – Penthièvre beach dune system, analyses performed from the use of spatial data permit the identification of different coastal dynamics likely to control coastline variations as well as their spatial extent.

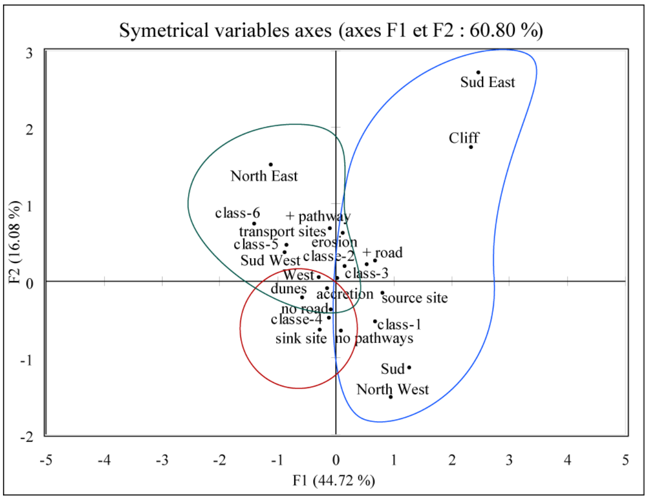


Figure 6: Variables and modalities projections over the two first axis obtained from the MCA (1952 – 2004)

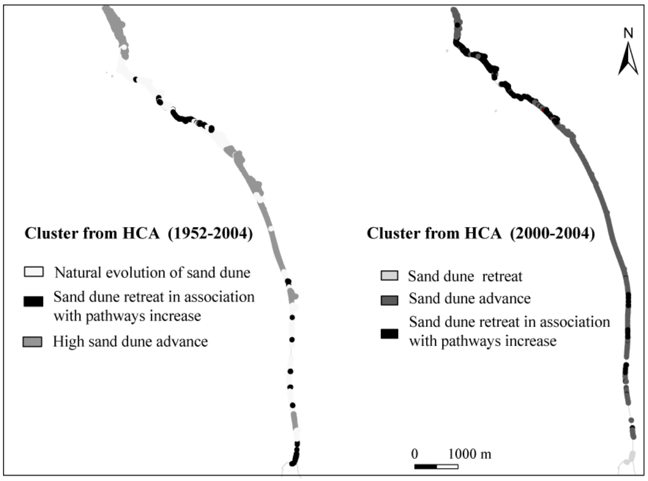


Figure 7: Clusters location obtained from HCA analyses

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