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Shoreline change patterns in sandy coasts. A case study in SW Spain

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ABSTRACT

Coastal changes on sandy shorelines are continuous and occur at diverse spatial and temporal scales. Gaining knowledge on beach change processes increases our capability to manage risks, especially shoreline erosion, affecting the increasing population living in coastal areas. Processes and factors involved in medium- and short-term beach changes depend on the morphological and dynamic characteristics of the coast. In this work, the decadal behaviour of 58 sandy beaches along the 150 km long South-Atlantic coast of Spain, between the Guadalquivir river mouth and the Strait of Gibraltar, is analysed in order to investigate the relationships between shoreline change patterns and the diverse morphological and dynamic factors controlling beach evolution in the area. For this purpose, georectified aerial photographs spanning the period 1956–2008 were compared in a GIS environment to calculate rates of shoreline change. Short-term evolution of beach profiles was also analysed in selected areas of interest.

Results show that the study area exhibits a great variety of shoreline evolution trends, with erosion prevailing in the northern and central sectors and stability or even accretion in the southern sector. In general, sediment availability is the main factor determining coastal erodibility in the area, largely conditioned by the reduction in fluvial sediment supply caused by river basin regulation. Nearshore bathymetry also has a great significance, as it controls wave refraction-diffraction patterns and wave energy concentration on certain zones. Human interventions on the coast also represent a major influence on beach erodibility in the study area. Severe detrimental effects are caused at certain points by shore-normal engineering structures blocking longshore drift. Additionally extensive urban development in backbeach environments has a significant influence on the sediment budget at certain areas.

On the basis of these results, a morphological and evolutionary classification of sandy beaches is proposed taking into account the way beach morphology influences erosion/accretion processes. Rectilinear beaches and enclosed beaches typically show dynamic equilibrium or even accretion trends, whereas reef-supported beaches tend to be dominated by erosion. Headland-bay beaches show complex evolution patterns greatly influenced by local conditions, such as specific shoaling processes or local winds. This classification is useful not only in forecasting general shoreline behaviour in the near future, but also in selecting the most appropriate type of intervention when managing retreating coasts.

1. Introduction

Sandy coasts are extremely dynamic geomorphic systems where continuous changes occur at diverse spatial and temporal scales. In the short term, coastal changes are related to fluctuations in wave energy and associated processes. On a long-term scale (centuries, millennia), coastal variability is mostly conditioned by relative oscillations of sea level and river sediment discharge, both mainly driven by climatic changes (Cowell and Thom, 1994; Paskoff and Clus-Auby, 2007). However, on an intermediate time scale (decades) factors influencing coastline changes are more complex and interrelated, including both natural and anthropogenic causes. In this regard, Komar (2000) emphasized the role of the sediment budget in coastal stability, particularly influenced by river watershed changes, river water use, river damming, jetties and breakwaters and shore protection structures, among others. At this scale shoreline and beach planform often vary quite rapidly in space and time. Causes for these variations are not always evident, thus rendering it difficult to develop predictions of future shoreline behaviour. Gaining knowledge on beach change at the intermediate time scale would increase our capability to manage risks affecting the increasing population living in coastal areas, especially those risks acting on a decadal basis such as medium-term shoreline erosion.

In fact, over the last decades coastal erosion is becoming a problem of increasing magnitude on the sandy shores of Spain (Sanjaume et al., 1996; Ojeda et al., 2002). Interventions aimed at addressing shoreline retreat processes are being included in coastal management plans in those areas where the "sun & sand" tourism model comes into conflict with a generally slow but continuous loss of beach sand. In this respect, long enough datasets of morphological historical records are

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necessary to investigate local and regional causes for coastal erosion, identify shoreline trends, detect types of coastal change and define sectors where coastline behaviour can be considered homogeneous over time (Crowell et al., 2005).

On embayed and pocket beaches affected by an active longshore current, patterns of shoreline change can in some cases be successfully predicted when triggered by human interventions on beach planform (e.g. construction of jetties). In these cases different numerical models can be applied with fairly good results (see Komar, 1998 for a synthesis). However, predictions on natural shores are much more difficult, due to the simultaneous occurrence of factors whose variability is not well known. One of these factors influencing medium-term behaviour of natural beaches is the geological framework. Beach boundaries, both emerged and submerged, exert a primary control on wave shoaling processes, refraction–diffraction processes and efficiency of longshore drift. Geological control influences every beach in a different manner, and can be responsible for significant deviations from predicted beach behaviour when applying traditional morphodynamic parameters (Jackson and Cooper, 2009). Although quantitative studies on recent shoreline changes and extrapolations for the future are relatively frequent (e.g. Dolan et al., 1991; Crowell et al., 1993; Guillén et al., 1999), literature about the role of geological controls on medium-term coastline behaviour is far less common (Riggs et al., 1995; Jackson et al., 2005; Lentz and Hapke, 2011).

In this work, the decadal evolution of sandy shores along the 150 km long South-Atlantic coast of Spain, between the Guadalquivir river mouth and the Strait of Gibraltar (covering the Atlantic side of the Cádiz province), is analysed in order to investigate the relationships between shoreline change patterns and the diverse morphological and dynamic aspects of the study area. The main objective is to gain a better understanding of the different factors that control erosion/accretion processes and evolution of beaches, by classifying beaches according to their characteristics and shoreline behaviour. This would help in the design of medium-term prediction models of shoreline change, ultimately contributing to a better assessment of hazards related to the use and evolution of coastal zones.

The case study used provides an ideal scenario for addressing the above issues by analysing factors influencing coastal evolution. The northern half of Cadiz coast is constituted by mesotidal, long rectilinear sandy shores, many of them highly developed, and close to major river mouths responsible for sediment supply to this coast. The southern half is represented by a microtidal, indented rocky coast with numerous small to medium-sized embayments, mainly natural and far from any significant sediment source.

Shoreline changes in the study zone are assessed by means of georectified aerial photographs from the period 1956–2008, along with the topographic monitoring of beach profiles in selected areas of interest. A simple classification of the sandy shore types and associated evolution trends existing in the area is proposed. This helps to understand the way coastal morphology influences erosion/accretion processes. It must be noted that cliff shores have not been included in this work unless fronted by a beach; in these cases only beach changes have been analysed (for cliff evolution patterns in the study area, see Del Río and Gracia, 2009; Del Río et al., 2009).

2. Study area

The Atlantic coast of the province of Cadiz extends for 150 km, between the Guadalquivir river estuary and the Strait of Gibraltar (Fig. 1). General coastal orientation is NW–SE with several W–E-oriented traits, so that long linear sectors alternate with embayments.

As a result of its geological framework the coast shows contrasting topography and morphology in the areas located north and south of Cape Trafalgar (Fig. 1). The Northern sector belongs to the end of the Guadalquivir Neogene Basin and is composed of soft, sub-horizontal sedimentary rocks. This gives rise to a generally linear, low coast with several wide embayments, controlled by Plio-Quaternary faults (Benavente et al., 2005a). Long sandy beaches and sandspits prevail, enclosing salt marsh areas like the Bay of Cadiz. The Guadalquivir River (the main watercourse in this coast) mouth is in this sector (Fig. 1). It is considered to be the main source of sediments to the eastern Gulf of Cadiz, although river discharge has been severely reduced since the 1960s–70s due to dam construction in its basin (Benavente et al., 2005a). The second river flowing into the study area is the Guadalete river, whose mouth is in the Bay of Cadiz (Fig. 1); also here several dams have been built in the last decades.

The Southern sector of Cadiz province belongs to the Betic Ranges, showing areas of moderate relief on Paleogene and Neogene detritic and calcareous units that were faulted and folded during Mio-Pliocene times. As a consequence, it is characterized by a young, indented coastline, with alternating cliffs and headland-bay beaches controlled by neotectonic features (Silva et al., 2006). Several minor watercourses flow into this sector, the most important of which is the Barbate river (Fig. 1).

Coastal setting determines prevailing winds in the study area to blow from East-SE (*Levante*) and West-SW (*Poniente*) directions. Warm and dry *Levante* winds blow from the Mediterranean Sea, with high frequency and velocity, especially near the Strait of Gibraltar. These characteristics control the strong influence of easterly winds in aeolian sediment transport in the study area; however, the importance of *Levante* as wave-generating wind is greatly reduced by its short fetch (Gracia et al., 2006). On the other hand, humid *Poniente* winds have a lower influence on aeolian transport, but due to the long fetch they reach great significance in wave generation, especially during winter storm conditions (Benavente et al., 2005a).

Both sea and swell waves generally approach the coast from the West, although SW waves usually have greater importance during storms (Del Río et al., 2012). The highest waves appear in winter associated to Atlantic low pressure systems, when they can reach significant heights of up to 4 m. However, over 70% of annual waves are less than 1 m high, so Cadiz littoral can be classified as a low-energy coast (Benavente et al., 2000). General wave conditions slightly shift southwards of Cape Trafalgar, due to changes in coastal orientation and to the higher relevance of *Levante* winds. Consequently, near the Strait of Gibraltar SE waves have greater importance, and *Poniente* waves show relatively lower frequency and height. Longshore drift in the study area generally flows in a SE direction because of the prevalence of westerly waves. In the southern Cadiz coast, reduced westerly waves, lower sediment supply and the presence of headlands cause an important decrease in the efficiency of the longshore component of sediment transport by waves.

Tides in the study area are of semidiurnal type, and tidal range gradually diminishes towards the Strait of Gibraltar. The Northern and central sectors are mesotidal coasts according to Davies (1964), with a MSTR (Mean Spring Tidal Range) of 2.96 in Cadiz city (Benavente et al., 2007). From Cape Trafalgar southwards, the narrowing of the continental shelf (Fig. 1) and the proximity of the Mediterranean Sea produce a sharp reduction in tidal range, so MSTR decreases from 2.30 m in Barbate to 1.22 m in Tarifa (Benavente et al., 2007); therefore, the Southern sector of the coast is a microtidal area according to Davies (1964).

3. Methods

Medium-term beach changes in the study area were assessed by means of 10 sets of aerial photographs and orthophotographs spanning between 1956 and 2008, at scales from 1:15,000 to 1:33,000 (Table 1). Due to the great extent of the study area, spatial coverage of each photogrammetric flight was not complete, so a total of 6 sets from different dates were analysed on each coastal sector in order to use homogeneous sources of information. The nearly 300 photographs available were examined through stereoscopic photointerpretation, digital photogrammetry