Ocean & Coastal Management 124 (2016) 84–99

Contents lists available at ScienceDirect

Ocean & Coastal Management

journal homepage: www.elsevier.com/locate/ocecoaman

Decadal evolution of coastline armouring along the Mediterranean Andalusia littoral (South of Spain)

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A R T I C L E I N F O

Article history:
Received 30 November 2015
Received in revised form
8 February 2016
Accepted 13 February 2016
Available online 2 March 2016

Keywords:
Armouring
Erosion management
Protection structures
Ports
Tourism

A B S T R A C T

Emplacement of hard coastal defence structures, such as seawalls, revetments, groins and breakwaters, or even ports, harbours and marinas, is commonly known as coastline armouring. This paper deals with coastal armouring evolution along the 546 km Mediterranean coast of Andalusia (Spain). It is based on photo interpretation and GIS tools, which have been employed to map coastal structure emplacement and evolution by analysis of 1956, 1977, 2001 and 2010 aerial photos. Additionally the coefficient of infrastructural impact K, which represented the relation between the total length of maritime structures and the length of the study coastal section, was obtained - i.e. *minimal* at $0.001 \leq K < 0.1$; *average* when $0.1 \leq K < 0.5$; *maximal* at $0.5 \leq K < 1.0$ and *extreme*, when $K \geq 1.0$.

In the mid 50s, coastal zones presented a very low level of armouring and the most important settlements were coastal towns and associated fishing communities. The total length of anthropogenic structures, 11 ports and a few protection structures, gave rise to K values ranging from “minimum” (with average $K = 0.07$) to K “extreme” ($K = 2.5$ in 8 sectors).

During the 60s and 70s, the armoured coastline length increased from 42.1 (1956) to 98.2 km (in 1977). The “minimum” K value maintained the same average value (0.07) but affected 10 sectors. The “extreme” K value increased the average value to 3.6 and affected 25 sectors. The above was essentially linked to coastal tourism development under an extreme *laissez-faire* politico-economic regime: several ports were enlarged and new marinas constructed specially along the Costa del Sol. Induced coastal retreat processes were counteracted by progressive groin emplacement to enlarge tourist beaches and/or halt coastal erosion: 42 groins and 1 breakwater in 1977, some 8 fold increase with respect to 1956. Revetments and seawalls occupied a total amount of 7.6 km.

Coastal occupation modalities from the mid 70s to 2001 were similar to the previous period. The armoured coastline length increased from 98.2 to 182.3 km, with “minimum” K values (average: 0.09) recorded in 15 sectors and “extreme” values (average $K = 4.7$) recorded in 33 sectors. Coastal occupation and tourism development did not record significant improvements during 2001–2010 and K values recorded a small increase.

Approaches used to halt beach erosion were coastal structures as coastal tourism was the main beach management target, carried out essentially by increasing beach carrying capacity without consideration of ecological and environmental aspects. In the last few decades, coastal defence policies experienced important changes based on reshaping/removal of hard structures and the realization of nourishment.

1. Introduction

Human occupation along coastal areas has greatly increased in past decades and approximately 50% of the world coastline is

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http://dx.doi.org/10.1016/j.ocecoaman.2016.02.007
0964-5691/

currently under threat because of excessive development (Finkl and Kruempfel, 2005) especially linked to tourism related activities, one of the world's largest industries (Klein et al., 2004; Houston, 2013). Associated with ongoing tourism development in Europe, is the high level of armouring of shorelines by coastal defences and harbours (Griggs, 2005; Charlier et al., 2005; Pranzini and Williams, 2013), with especially high percentages of armoured shoreline in the North Sea (16%) and the Mediterranean Sea (more than 8%; EEA, 2006). In the Mediterranean region, tourism is the most important activity with 298 million international tourist arrivals in 2008, followed by approximately 400 million domestic tourist arrivals. In many Spanish coastal areas the built up zone exceeds 45% (EEA, 2006), with tourism receipts accounting for some 5% of the gross domestic product (WTO, 2006). Spain plus Italy, France, Greece and Turkey account for "the most significant flow of tourists. . . . a Sun, Sea and Sand (3S) market" (Doods and Kelman, 2008) and 'Travel & Tourism' worldwide, is expected to grow at a level of 4.0% per year over the next ten years. In the Mediterranean coast, one of the fastest rates of urban development over the last decades has been observed along the Spanish littoral, especially in the Costa del Sol where population rose by over 10% per annum between 1950 and 1991 (Malvárez et al., 2000), reaching in 2006 a total amount of 1,136,712 inhabitants (Malvárez, 2012). Population enhancement continued at an annual rate of 9.2% between 2006 and 2011 such an increase corresponding to 50% of the demographic increase recorded along the whole Andalusia littoral during the same period (Romero Martínez et al., 2015). Nowadays Costa del Sol receives c. 10,000,000 visitors per annum, i.e. 35% of all Andalusia visitors, making it one of the most important tourist destinations in Spain.

The protection of built-up areas and halting shoreline recession has largely been carried out by constructing hard defence structures mainly consisting of groins, jetties, breakwaters, revetments and seawalls (Malvárez, 2012). Common problems associated with the emplacement of harbours, ports and coastal defence structures, are stabilization of the directly involved coastline and increasing downdrift erosion. "Coastal squeeze" (Doody, 2004), i.e. the impossibility of coastline landward migration because of seawalls or other man-made structures, takes place when coastal erosion processes related to reduction in river sediment input, sea level rise and increasing storminess (Jones and Phillips, 2011), which can cause the complete disappearance of the beach/salt marsh whilst deepening nearshore areas fronting coastal structures (Pilkey and Dixon, 1996; Doody, 2004). The decreased ability to respond to natural change also occurs when coastal defences at the base of eroding cliffs cuts off sediment supply to beaches alongshore (Runyan and Griggs, 2003).

The development of erosion processes in downdrift areas is usually countered by the progressive addition of engineering structures according to the "domino" effect (Cooper et al., 2009), a frequent process observed in many Mediterranean areas (Zviely and Micha, 2003; Sabatier et al., 2009; Anfuso et al., 2012). As a result of the above, emplacement of man-made beach constructions generally produces risks of deaths because of dangerous currents, loss of ecological value, decreases in biodiversity and diminution of landscape value (Williams and Micallef, 2009; Williams et al., 2012). In recent decades, beach nourishment works have been implemented: from 1983 to 2000 more than 600 fills and refills have been installed along the Spanish coast in order to curb coastal erosion, especially on the Mediterranean coast (Hanson et al., 1994; Cooper and Alonso, 2006).

The case study presented here deals with the description and evolution of ports and coastal protection structures, as well as assessment of their impact (*K*, Aybulatov and Artyukhin, 1993), along the Mediterranean coast of Andalusia (Spain) using four sets of aerial photographs from 1956 to 2010.

2. Study area

The *circa* 546 km of the Andalusia Mediterranean coast of SW Spain extends from Gibraltar Strait to the Murcia region and administratively includes the provinces of Cádiz, Málaga, Granada and Almeria (Fig. 1). The landscape is dominated by the well-developed Betic Chain, which reaches high elevations close to the coast, as well as by several, small coastal plains, especially extended at the mouth of numerous rivers and *ramblas* (gullies linked to the steep slopes) that drain the Chain.

The coastline is composed by elongated sand and rocky sectors, which often give rise to headlands forming pocket beaches (*calas*) of different size and composed of medium-coarse dark or golden sands and gravel/pebbles close to *ramblas* mouths (Williams et al., 2012). Especially under episodic heavy rainfalls, reworked fluvial sands and gravels constitute important sediment supplies to the beach system. During the last decades, river basin regulation plans involving water management for tourist and agricultural purposes, has brought about dam and reservoir construction that have systematically limited such supplies to the coast (Guisado and Málvarez, 2009).

The nearshore region usually has high slope values and beaches generally show intermediate to reflective morphodynamic states (Guisado and Málvarez, 2009). It is a micro-tidal, semidiurnal environment (tidal range <20 cm, Guisado et al., 2013) exposed to winds blowing from SE to SW with minimum and maximum velocities ranging from 0.4 to 9.0 m/s. Wave data was obtained from directional offshore deep water (530 and 368 m depths) wave buoys situated in the Alboran Sea and Cabo de Gata (Fig. 1), which belong to the coastal buoy network operated by *Puertos del Estado* (Spanish Ministry of Public Works). Waves essentially approach from easterly directions and show a clear seasonal behaviour with storm conditions being recorded during November–March (winter season; Pita López, 2003; Guisado et al., 2013). Specifically, the Alboran Sea buoy includes >80% of significant wave heights (H_s) lower than 1 m and a peak period (T_p) of 5 s - approaching essentially from ESE, E and SW. More energetic waves (H_s >2.5 m, $T_p = 8$ s) approach from the East. Similar wave records are recorded by the Cabo de Gata buoy, but also indicate a WSW direction of wave approach, which acquires more importance especially in winter and spring months.

Due to coastline orientation, predominant easterly winds and associated storm waves give rise to sea wave conditions generating a prevailing westward littoral drift (Pita López, 2003). Winds from western directions and associated sea waves as well as swell waves that only rarely filter from the Atlantic Ocean, give rise to an opposing drift, which achieves particular importance in certain coastal sectors and/or periods (Guisado et al., 2013).

3. Methods

Photo interpretation and Geographic Information System (GIS) methods were applied for data processing and mapping defence structures and ports and harbours in order to assess the impact of structures on the investigated coast. All estimations and analysis have been implemented on aerial geo-referenced photographs taken in 1956, 1977, 2001 and 2010 (Table 1), available on-line at the Junta de Andalusia web site (http://www.juntadeandalucia.es/, accessed March 2015). The 1956 and 1977 photographs were geo-referenced and computer-rectified to eliminate scale and distortion effects (Crowell et al., 1993; Moore, 2000). Ground Control Points (GCPs) for photo registration were obtained from the geo-referenced orthophotos of 2010, and all information has been