Ecological Indicators 71 (2016) 302–316

Contents lists available at ScienceDirect

Ecological Indicators

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

Coastal-flood risk management in central Algarve: Vulnerability and flood risk indices (South Portugal)

A.M. Martínez-Graña[a,*], T. Boski[b], J.L. Goy[a], C. Zazo[c], C.J. Dabrio[d]

[a] Department of Geology, Faculty of Sciences, Square Merced s/n, 37 008 Salamanca, University of Salamanca, Spain
[b] Centre for Marine and Environmental Research CIMA, Edifício 7, Campus Universitário de Gambelas, Universidade Algarve, 8005 Faro, Portugal
[c] National Museum of Natural Sciences, Section Geology, Street José Gutiérrez Abascal n◦ 2, 28006 Madrid, Spain
[d] Department of Stratigraphy, Faculty of Geology, Complutense University, 28040 Madrid, Spain

ARTICLE INFO

Article history:
Received 3 March 2016
Received in revised form 12 July 2016
Accepted 14 July 2016

Keywords:
AVI Index
FRI Index
Flood risk
Vulnerability
Coastal management
GIS

ABSTRACT

This paper presents an analysis of the vulnerability (AVI Index) and hazard of flooding by sea level rise (FRI Index) in the central Algarve (South Portugal), between the cities of Portimão and Tavira, which is an area of intense urban impact and fast growing tourism. The vulnerability index was calculated using the following parametric thematic maps: lithology, geomorphology, slopes, elevations, distances, bathymetry, variations of the coastline, wave height and activity, variations of sea level and tidal range. The AVI Index was validated by the results obtained from the analysis of the risk of flooding from the FHI Index applied to several time horizons (X_0-present, X_1-100 years, X_2-500 years, X_3-1000 year, X_4-Storm and X_5-Tsunami). Application of GIS and remote sensing techniques, viz. spatial analysis, interpolation processes and geostatistical analysis, permitted a regional forecasting model of change in the mean sea level and the ensuing consequences to be established. Analysis of the obtained results shows an increase in potential flood zones in populous coastal tourist areas with a high risk of exposure and a significant spatial extent of 8.84 km^2 only in Faro municipality. The assessment and delineation of other endangered sectors could contribute to designing appropriate long- term management policies for the coastal of Central Algarve.

1. Introduction

The paradigm of “Global change” is a subject that has attracted the attention of the scientific community for decades and became a truly hot topic after the 1982 Rio de Janeiro Earth Summit. Often climate change and global change are equated, and climate and “global warming” are commonly used as an all in one explanation for all sorts of changes or processes currently taking place at the Earth’s surface (Zazo, 2015).

According to the latest report by the Intergovernmental Panel on Climate Change (IPCC, 2014), the warming of the climate system is unequivocal. Since 1950 there have been unprecedented changes in the climate systems, which can be seen in both the observational historical records, from the late nineteenth century, and with paleoclimatic records spanning the last millennia. These changes are manifested, by the warming of the atmosphere and oceans, decrease in the mass of cryosphere, and by an increase in the concentrations of atmospheric greenhouse gases, among other types of processes.

Global studies of the current sea level indicate a sustained rise that has occurred since the late nineteenth century, with a turnaround and acceleration in the second half of the twentieth century. This trend can be seen in tide gauge records since 1880, and has been largely confirmed by the sea surface elevation data recorded by several altimetric satellite missions: Topex-Poseidon, Jason I, and OSTM-Jason II (Tooley and Jelgersma, 1992; Church and White, 2011). The available figures obtained from the tide gauges point to a rate of increase around of 2.8 ± 0.8 mm/year, whereas values provided by satellite missions amount to 3.2 ± 0.4 mm/year (Church et al., 2013).

The physical phenomena behind the rise of the global average sea level are primarily ocean thermal expansion and the melting of glaciers. Tectonics and salinity only have a local influence (Table 1).

There is a wide variability in projections of future sea level rise, which have been estimated as: 21–48 cm (Meehl, 2007), 50–135 cm (Bindoff et al., 2007; Rahmstorf, 2007), 60–115 cm (Vellinga and

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[*] Corresponding author.
E-mail addresses: amgranna@usal.es (A.M. Martínez-Graña), tboski@ualg.pt (T. Boski), joselgoy@usal.es (J.L. Goy), mcnzc65@mncn.csic.es (C. Zazo), dabrio@ucm.es (C.J. Dabrio).

http://dx.doi.org/10.1016/j.ecolind.2016.07.021

Table 1
Contributions to the balance of sea level since 1972 (Church et al., 2013).

Components	1972–2008 (mm/year)	1993–2008 (mm/year)
Tide-gauge (Total)	1.83 ± 0.18	2.61 ± 0.55
Tide-gauge and altimeter (Total)	2.10 ± 0.16	3.22 ± 0.41
1. Thermal expansion	0.80 ± 0.15	0.88 ± 0.33
2. Glaciers and ice sheets	0.67 ± 0.03	0.99 ± 0.04
3. Ice of Greenland	0.12 ± 0.17	0.31 ± 0.17
4. Antarctic ice	0.30 ± 0.20	0.43 ± 0.20
5. Terrestrial storage	−0.11 ± 0.19	−0.08 ± 0.19
Sum of components (1 + 2 + 3 + 4 + 5)	1.78 ± 0.36	2.54 ± 0.46

Wood, 2008), 85–200 cm (Pfeffer et al., 2008), 60–95 cm (Kopp et al., 2009), 80–190 cm (Vermeer and Rahmstorf, 2009), 78–160 cm (Grinsted et al., 2010), >100 cm (Katsman and Oldenborgh, 2011) for the XXI Century During the period 1901–2010, the global mean sea level raised an average of 1.7 [1.5–1.9] mm/year, a rate higher than that of the previous two millennia (Church et al., 2013).

The projections of the change in sea level at a regional scale, suggest that it is very likely that in the XXI century and later, changing sea levels will have a pronounced regional pattern, with significant deviations from the global average. In the Fifth Assessment Report (Conde, 2015; Church et al., 2013; IPCC, 2014), it is postulated that during decadal periods, these regional variation rates resulting from climate variability, may differ by more than 100% from the global average.

There is growing public awareness of the impacts that climatically driven environmental changes may have on the socio-economic sphere. For instance, The European Union's directive 2007/60/EC (DOUE 60, 2007) was promulgated due to the increased frequency of catastrophic events—213 major flooding events with 1126 deaths and the loss of 52 billion Euros (Jonkman and Kelman, 2005). Currently, there is a need for a renewed assessment policy and flood risk control measures in all of the member states, both in coastal and inland Settings. To manage the risk offloods, a detailed analysis of the variables affecting the current sea level rise is required in order to develop a reliable simulation model, and mapping (Kurt et al., 2004, 2011; Kulkarni et al., 2014). Such mapping is, a very effective tool, that is widely used in planning and environmentally-oriented land management.

The Algarve coastline is vulnerable to sea level rise, and in particular along beaches, deltas, tidal flats and coastal wetlands. Human activity in these areas, especially tourism, brings about additional challenges in terms of increasing vulnerability and degree of exposure to the hazard. Therefore a study involving short and medium-term flood risk is most needed. Widespread flooding of Albufeira in November 2015, during the torrential precipitation associated to a storm surge was reported to have caused material losses in excess of 10M euro, and is a clear example of the need for prevention plants. Likewise, estimating the possible rise in sea level, whatever the timescale, may prevent or, at least, induce protection and mitigation measures, both in structural and land use planning terms, aimed to minimize the presumable social impacts involved. It is estimated that, worldwide, some 200 million people live in coastal areas, a figure expected to rise up to 600 million in 2100 (Nicholls and Mimura, 1998).

The objectives of this study were to assess the degree of vulnerability to changes in sea level and the risk of flooding in the coastal sector between Portimão and Faro in central Algarve (South Portugal) (Fig. 1). The study area, includes two clearly differentiated sectors: to the east the Ria Formosa tidal flats laying behind the protecting sandy spits and barrier islands that migrated under an eastward-moving longshore drift (Andrade et al., 2004); and to the west, the mostly rugged coastline extending between the cities of Portimão and Albufeira, with beaches and urban areas protected by rocky outcrops.

Vulnerability was calculated using empirical methods that combined a series of integrated factors from parametric maps, from the Algarve vulnerability index –AVI-created by the authors based on Ojeda et al. (2009) changing some parameters for the Algarve area using GIS (ArcGis v10.3). For the purpose of the flood risk analysis deterministic methods were used by assigning a probability of sea level rise based on a variety of foreseeable temporal scenarios (100 years, 500 years, 1000 years, storms and tsunamis).

2. Material and methods

2.1. Vulnerability analysis for coastal flooding

The vulnerability was assessed by means of the Algarve vulnerability index—AVI-, similar to that used by the US Geological Survey (Hammar-Klose and Thieler, 2001) applied to the American Atlantic coast, Pacific and Gulf of Mexico, and also validated in the Spanish Andalusian coast near the area of the present study (Ojeda et al., 2009). This index was adapted and modified according to the intrinsic parameters of the study area, considering ten factors that made up the index AVI equation (Eq. (1)) and are explained below:

$$\mathrm{AVI} = \sqrt{\mathrm{Fl}} \times \mathrm{Fg} \times \mathrm{Fs} \times \mathrm{Fh} \times \mathrm{Fd} \times \mathrm{Fb} \times \mathrm{Fc} \times \mathrm{Fw} \times \mathrm{Fsl} \times \mathrm{Ftr}/10 \qquad (1)$$

2.1.1. Lithologic factor (Fl)

This factor created a parameter which indicated the resistance of rock units against marine erosion.

From a geological point of view, two different areas (Manuppella et al., 2007) are recognized along the Algarve coastal fringe: a northern area with carbonate Mesozoic formations and a southern one, where diversely consolidated detrital sediments of Cenozoic age predominate. These terrains are easily and immediately differentiated by their topographic relief. The oldest materials correspond to the Late Triassic evaporitic marls that evolved into salt diapirs under the cities of Faro and Loulé. During the Jurassic period, fossiliferous carbonate formations with abundant marine fossils were deposited, with an erosional event in the Middle Jurassic. Cretaceous carbonates lay unconformably on top. N-S faults promoted tilting of blocks. During the Miocene, biocalcarenites (Pais et al., 2012) with abundant marine fossils and sandstones with interbedded glauconitic silts accumulated, heavily deformed by the undergoing diapirism. Five Plio-Pleistocene (Moura and Boski, 1999; Moura et al., 2009) fluvial to marine units accumulated on a karstified surface of Miocene age (Pereira and Cabral, 2002). In ascending stratigraphic order, these are: Falesia feldspathic sands, Montenegro burrowed sands of Montenegro, Quarteira orange sands, Ludo yellow sands, and Gambelas pebbly sands. There are also gravel terraces and fluvial channel-fills of Pleistocene age covering Jurassic limestones. Finally during the recent Holocene, coastal sands accumulated as beaches and dune systems, barrier islands, and silts as tidal flats and tidal marshes of the sheltered channels of Ria Formosa. Terrestrial deposits accumulated in alluvial river channel, flood plains and low terraces.

For the analysis of the lithological factor, the geological materials are grouped into five classes according to the "hardness" against a possible arrival of the sheet of water. Then, the most recent unconsolidated materials (grain sand, gravel, etc.) have less resistance to the effect of the water surface meaning sectors more vulnerable to an advance of the sea than the most consolidated lithologies: basalts (value 1), limestones and marls (value 2), are more resistant to ascending sea level than biocalcarenites and sandstones (value 3), conglomerates, clays and silts (value 4) and sand and gravel (value 5) (Fig. 2).