ASSOCIAÇÃO PORTUGUESA DOS RECURSOS HÍDRICOS
APRH

Journal of Integrated Coastal Zone Management (2022) 22(3): 225-239
© 2022 APRH
ISSN 1646-8872
DOI 10.5894/rgci-n546
url: https://www.aprh.pt/rgci/rgci-n546.html

HAZARD MAPPING BASED ON OBSERVED COASTAL EROSION RATES AND DEFINITION OF SET-BACK LINES TO SUPPORT COASTAL MANAGEMENT PLANS IN THE NORTH COAST OF PORTUGAL

Francisco Taveira-Pinto[1] *, Renato Henriques[2], Paulo Rosa-Santos[1], Tiago Fazeres-Ferradosa[1],
Luciana das Neves[1, 3], Francisco V. C. Taveira Pinto[1], Maria Francisca Sarmento[1]

ABSTRACT: Coastal zone management plans need to consider scenarios of coastline evolution and associated uncertainties. In this paper, the main causes of shoreline retreat and coastal erosion (natural and anthropogenic) in the north coast of Portugal are discussed. The importance of increasing knowledge on coastal dynamics to improve long-term predictions of coastline changes is highlighted since it is essential to establish proper management tools. It is also shown that the Portuguese coastal ecosystems are not resilient enough to extreme events and that the Portuguese coastal zone, like very many others worldwide, and will be severely affected by the effects of climate change. It is concluded that extreme events need to be properly characterized and their impacts assessed since they have important implications in terms of uses of either the coastal zone or the coastal waters. Without that analysis, coastal management plans will be lacking technical and scientific information and data that could help decision-makers define the best strategies to control erosion levels and the impact of extreme events related to climate change effects. Finally, a detailed assessment of the coastline evolution was performed for the new *Caminha-Espinho* coastal management program, for the time horizons 2050 and 2100, based on historical data. The methodology used for the evaluation of the rates of shoreline change, hazard mapping and definition of set-back lines is presented. Selected examples are given to demonstrate the potential of this methodology in supporting the development of coastal zone management plans, but also to highlight the limitations and uncertainties linked to the complexity of the phenomena under analysis.

Keywords: coastal management programs, climate change, set-back lines, extreme events, *Caminha-Espinho* stretch.

RESUMO: *Os planos de gestão da zona costeira devem considerar os cenários de evolução da linha costeira e as incertezas associadas. Neste artigo, são discutidas as principais causas do recuo da linha de costa e da erosão costeira (naturais e antropogénicas) na costa norte de Portugal. A importância de aumentar o conhecimento sobre a dinâmica costeira de forma a melhorar as previsões a longo prazo das alterações costeiras é realçada, uma vez que este é essencial para estabelecer ferramentas de gestão adequadas. Mostra-se, também, que os ecossistemas costeiros portugueses não são suficientemente resilientes a eventos extremos e que a zona costeira portuguesa, à semelhança de muitas outras no mundo, será severamente afetada pelos efeitos das alterações climáticas. Conclui-se que os eventos extremos necessitam de ser devidamente caracterizados e os seus impactos avaliados uma vez que têm implicações importantes em termos de usos, quer da zona costeira, quer das águas costeiras.*

Sem essa análise, os planos de gestão costeira terão em falta informação e dados técnico-científicos fundamentais para ajudar os decisores a definir as melhores estratégias para controlar os níveis de erosão e o impacto de eventos extremos relacionados com os efeitos das alterações climáticas. Por fim, foi realizada uma avaliação detalhada da evolução da linha de costa para o novo programa de gestão costeira Caminha-Espinho, para os horizontes temporais 2050 e 2100, com base em dados históricos. É apresentada ainda a metodologia utilizada para a avaliação das taxas de alteração da linha de costa, mapeamento de perigos e definição de linhas de recuo. Exemplos selecionados são apresentados para demonstrar o potencial desta metodologia no apoio ao desenvolvimento de planos de gestão da zona costeira, mas também para destacar as limitações e incertezas associadas à complexidade dos fenómenos em análise.

Palavras-chave: *programas de gestão costeira, alterações climáticas, linhas de recuo, eventos extremos, troço Caminha-Espinho.*

---

1 Faculty of Engineering of the University of Porto and Interdisciplinary Centre of Marine and Environmental Research of the University of Porto, Portugal, email*: fpinto@fe.up.pt; pjrsantos@fe.up.pt
2 Department of Earth Sciences, University of Minho and Institute of Earth Sciences, Portugal, email: rhenriques@dct.uminho.pt
3 International Marine and Dredging Consultants (IMDC), Belgium

Submission: 4 JAN 2023; Peer review: 13 JAN 2023; Revised: 3 FEB 2023; Accepted: 6 FEB 2023; Available on-line: 27 MAR 2023

1. INTRODUCTION

The Portuguese continental coastline is approximately 987 km long, mostly sandy, with around 60% of its extension composed of sandy dunes. Several estuaries, small river discharges, rocky areas, cliffs, urban areas, ports and coastal aquifers can also be found along the coast, Figure 1. In some stretches, nearshore rocky outcrops provide natural shelter to the coast (Rosa-Santos *et al.*, 2009).

Since the 1970's, Portuguese coastal areas experienced rapid and significant economic growth and development. Nowadays, about 75% of the Portuguese population lives in the coastal zone and about 14% less than 2 km from the coastline at high tide (APA, 2017). This number is still growing, which leads to important impacts in both estuarine and coastal waters, as it is shown in Figure 2 and Figure 3, for, respectively, Pedra Alta and Pedrinhas.

It is important to note that around 14% of the Portuguese continental coastline is artificialized due to the presence of coastal structures (*e.g.*, groins, revetments or port breakwaters), 25% is affected by coastal erosion and there is a potential risk of loss of territory in circa 67% of the coastline (Lança, 2020).

The Portuguese coastline is divided into coastal stretches having each one a coastal management plan associated, namely the *Planos de Ordenamento da Orla Costeira* or the more recent *Programas da Orla Costeira*. These management plans have not always been effective in controlling the multiple impacts of the very many activities that are carried out in coastal areas and putting into practice measures to protect, preserve and improve the quality of coastal waters, namely as per stipulated in the Water Framework Directive (EC, 2000). Notwithstanding, a significant length of the Portuguese coastline is still in a relatively natural state.

Some coastal areas have today a better management strategy in terms of conservation and development. An increased interest of national and local authorities in protecting coastal areas and waters from human activities has been observed, especially close to beaches and urban areas at risk. São Bartolomeu do Mar is a good example of a planned retreat respecting the history, social, cultural and economic aspirations of local communities, Figure 4. The interventions carried out in São Bartolomeu do Mar included the demolition of existing buildings (27 in total) and the nature restoration in degraded and/or unoccupied areas, with soil decompaction, dune recovery, planting of

Figure 1. Examples of coastal stretches from the Portuguese coast.

Figure 2. Pedra Alta, Viana do Castelo: evolution from 1965 to 2021 (Google Earth images).

Figure 3. Pedrinhas, Esposende: evolution from 1965 to 2021 (Google Earth images).

autochthonous species and the installation of sand-retention fences. The interventions also included the requalification of the urban seafront and the consolidation of structural elements that were degraded, considering local cultural and religious heritage and traditions.

Climate change is important to consider in future coastal zone planning, mainly because it is associated to extreme events (*e.g.* more frequent storms, higher wave heights and periods, changes in wave direction, increased mean sea level and changes in wind direction) that will cause relevant impacts on coastal waters and coastal aquifers, with increased erosion rates, salt water intrusion and water quality deterioration (Taveira-Pinto *et al*., 2021a). Due to those extreme events, several coastal areas will face higher risks, due to increasing overtopping and issuing flooding, more rapid erosion at higher erosion rates and other related phenomena, all combined with ongoing sediment starvation from natural and human-induced causes. For these reasons, the management of coastal areas needs to adapt to present challenges, in order to allow the required increase in coastal resilience and safety against extreme events (Taveira-Pinto *et al*., 2021b).

Coastal erosion, *i.e.*, the advance of the sea in relation to a reference coastline, with generally known causes, should be evaluated and analyzed as an average over a given period of time. This period should be long enough to eliminate seasonal variations related to tidal range, weather, storms and local sediment dynamics. Nowadays, the analysis of historical aerial photographs using tools such as the DSAS – Digital Shoreline Analysis System (an add-in software within the Environmental System Research Institute – ESRI, ArcGIS©) (Nave and Rebelo, 2022), eventually combined with topo-hydrographic and LiDAR surveys (Bio *et al*., 2020), allows to assess the coastline evolution and to calculate a range of statistical parameters that characterize that change.

Recently, during the revision of *Caminha-Espinho* coastal management program, the rates of shoreline change were assessed considering historical coastline evolution data and anecdotal evidence of areas prone to overtopping and flooding. While developing this coastal management program, which encompasses a coastal stretch with a length of approximately 120 km, the influence of extreme storm events, expected mean sea level rise, overtopping and flooding were considered, as

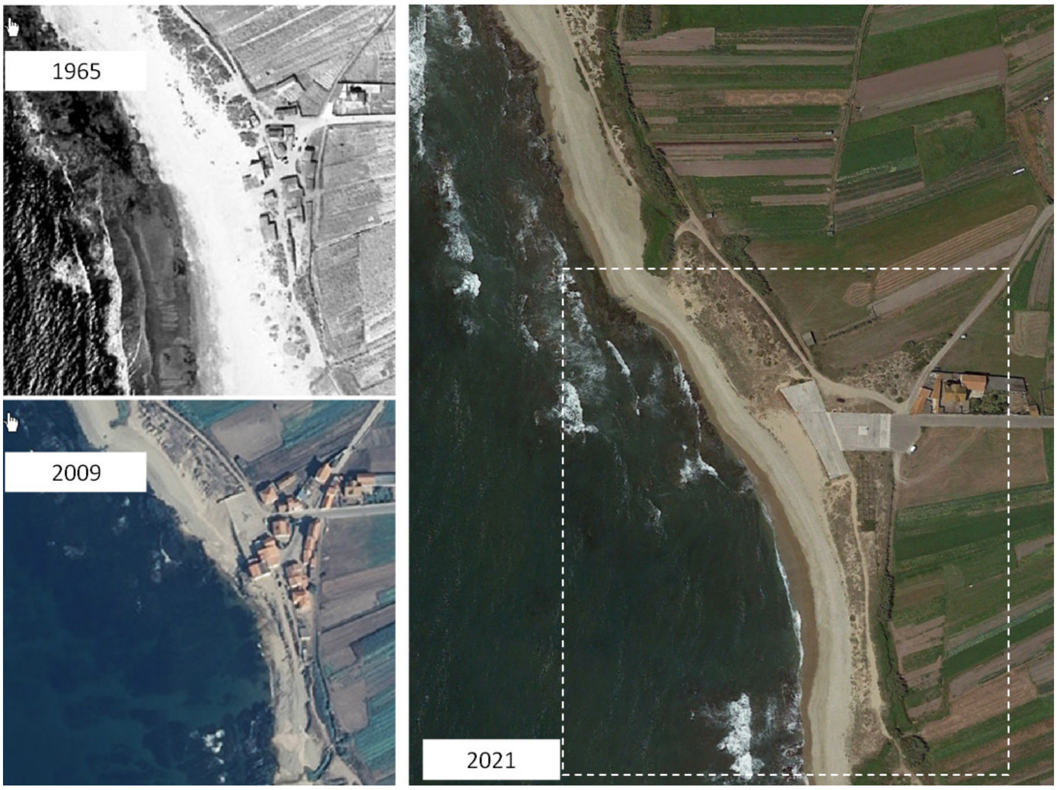

Figure 4. São Bartolomeu do Mar, Esposende: Evolution from 1965 to 2021 (Google Earth images).

well as precautionary measures for safeguarding of people and assets in vulnerable areas.

Following this introduction, an overall characterization of *Caminha-Espinho* coastal stretch is presented in section 2. The main anthropogenic effects on the Portuguese shoreline are discussed in section 3 whereas the methodology used in the calculation of the rates of shoreline change, hazard mapping and definition of set-back lines the for 2050- and 2100-time horizons are described in section 4. The latter includes as well the obtained results and discussion.

In this paper, selected examples are presented to show the potential of the methodology used for hazard mapping based on set-back lines in supporting the development of coastal zone management programs, but also to highlight the limitations and uncertainties related to the complexity of the phenomena under analysis. The goal is to show the importance of increased knowledge on local coastal dynamics to improve long-term predictions of coastline change, to establish proper management tools, and to handle present and future coastal management challenges. As a matter of fact, recent extreme events have revealed that Portuguese coastal ecosystems are not resilient enough and therefore should be severely affected by the effects of ongoing climate changes.

2. GENERAL CHARACTERIZATION OF THE PORTUGUESE NORTHWEST COAST

The coastal zone is the interface between land and sea. Its significance and value are particularly relevant, namely in what concerns natural, human, economic and cultural assets. Its management is highly complex, due to natural hydro- and morpho-dynamics, diversity and vulnerability, as well as the interconnectivity of natural, economic and environmental systems. The following characteristics can be highlighted along the Portuguese NW coastal zone:

- beaches having a high recreational value, as well as delivering important coastal protection services;
- well-preserved beaches and dune ridges in some stretches;
- strong pressure for urban construction near the shoreline;
- generalized coastal erosion processes.

The wave regime in the NW Portuguese coast is of high energy, with offshore mean significant wave heights of circa 2-3 m, and mean wave periods of 8-12 s. In winter, storms generated in the North Atlantic are frequent and can persist for up to 5 days, with significant wave heights reaching 8 m (Veloso Gomes *et al*., 2006). In Leixões buoy, maximum waves higher than 14 m are often recorded during the winter season for wave directions between W and NW. Local storms can produce SW waves with up to 4 m of height, but the dominant wave regime is from W-NW (Veloso Gomes *et al*., 2006). Tides are semi-diurnal, with tidal ranges varying approximately from 2 m to 4 m, from neap to spring tides, respectively.

The sediment transport in the NW Portuguese coast is mostly associated with the littoral drift currents, originated from the waves that propagate to shore with a certain angle in relation to the coastline. Hence, waves, usually coming from NW, induce a dominant drift current directed from North to South (Rosa-Santos *et al*., 2009). This current may be inverted in some areas due to the presence of obstacles, namely south of estuary mouths protected by coastal structures (*e.g.*, breakwater, jetty, groin). At those locations, the sediment transport direction can change or be reversed by refraction and diffraction phenomena. Nevertheless, the annual mean balance is predominantly from North to South, as it can be verified directly through the accumulation of sediments in the northern zones of existent coastal structures, in contrast with the erosion that occurs in southern zones.

The coastal wind regime presents high seasonal variability. From April to August, WNW and NW winds are predominant, while in the other periods of the year the E-SSE wind is more frequent. W-SW winds are not frequent, although important during storm events. These local winds generate maritime currents and sea states with intensities and directions directly related to their velocity, persistence and direction. Even though important, those currents remain relatively small when compared to the currents associated with the wave action. The direct wind action is more significant on the emerged areas of the beach, namely on dunes.

In the Portuguese NW coast, erosion is mainly the result of the weakening of river sediment sources in recent decades (Santos *et al*., 2017). Less sediment is now being supplied to the coast due to damming in rivers of Portugal and Spain, regularization of the river banks and maintenance dredging to maintain service draughts in existing navigation channels and sand mining for construction, as well as land use change and urbanization.

Portuguese sandy coasts are thereby eroding because the potential transport capacity of waves – between 1 and 2

Mm^3/year – is much higher than the annual sediment volume supplied by the rivers – now up to 0.2 Mm^3/year (Veloso Gomes *et al*., 2006). Sea level rise due to global eustatic effects associated with climate change, at an average rate of approximately 1.5 mm/year (observed during the 20th century), also contributes to the decrease of the sedimentary supply of the rivers to the coast by the induced change in their equilibrium profile. Regional effects, related to climate change and coastal subsidence are also accepted causes of shoreline retreat (Bruun, 1962). Erosion along the Portuguese coast can also be traced back to the construction of sea ports, not just because of maintenance dredging taking sediment out of the system, but also because of long enough outer breakwaters intercepting the littoral transport and inducing erosion problems in adjacent shorelines due to the lack of natural nourishment.

3. SHORELINE AND COASTAL RESPONSE TO ANTHROPOGENIC FACTORS

To adequately manage the coastal zone, it is necessary to understand the effects of both relevant physical processes and anthropogenic factors, since these effects will allow defining short and long-term scenarios for shoreline change and risk analysis (Dean, 2008). The impact of anthropogenic factors on the Portuguese coastal zone has become significant in recent decades. Furthermore, both spatial and temporal scales of such impacts are anticipated to increase in the near future (Santos *et al*., 2017).

Erosion rates have been increasing during the last decades (mean shoreline retreats of up to 8 m/year in some stretches), with the exception of areas immediately updrift of existing transverse hard structures. More recently, this phenomenon has reached coastal stretches where there have been no records of erosion problems in the past. Hence, the extrapolation of historical erosion data to predict permanent loss of land in coming decades or centuries has to be carried out with caution, due to the complexity and nonlinearity of the involved physical processes.

Winters in the North Atlantic Ocean are often very severe (several strong storm events) and the shoreline of the Portuguese NW coast, during those periods, experiences several problems, mainly in the stretches where there is no natural protection (*e.g.*, rock outcrops). For example, a storm on January 3-7, 2014, caused damages in more than 40 locations along a coastal stretch of circa 120 km (Figure 5). Causes for said problems in several urban waterfronts, which are now more vulnerable to erosion and direct wave action, are often linked to:

- sandy beaches that are generally very narrow and dunes often presenting erosion bluffs;
- sandy beaches located updrift groins that have started losing sand (retreated) and downdrift in which erosion problems have aggravated;
- a high number of coastal protection structures (*e.g.*, groins and revetments) that are damaged or in bad condition.

Urban development (buildings, promenades, etc.) along waterfront in recent decades, sometimes on top of beaches and dunes, also contributed to changing morphological conditions, at least locally, increasing coastal risks. It should be noted here that in the 120-kilometre coastal stretch in analysis, *Caminha-Espinho*, there are 45 km of urban seafront and about 30 important beaches. The risk management in the past has been to construct groins or/and seawalls following disasters due to the exposure to ocean environmental conditions, however, more often than not, these coastal protection works have accelerated erosion problems further downdrift and have not precluded the continual process of coastal urban development. Quite the opposite, construction on top of dunes and sometimes beaches has assumed alarming proportions in some coastal municipalities, and uncontrolled urban expansion in coastal areas continued despite known and identified vulnerabilities. Urban development has also introduced changes to the natural coastal landscape, that has had detrimental impact on aesthetic ecosystem services. Unprotected beaches in *Caminha-Espinho* remain naturally dynamic and offer a big contrast to that. Recent efforts to deal with observed coastal environmental degradation through well-thought planning are encouraging; however, the level of land occupation in areas at risk and the need for restoring valuable coastal ecosystems may require more urgent measures and more difficult decision-making. This highlights the need to make a new revision of the coastal management plans supported by high spatial resolution data on erosion rates and exposure – *i.e.*, uses and land occupation on the hinterland – as well as on likely climate change scenarios.

4. COASTAL EROSION RATES AND HAZARD MAPPING

4.1 Introduction

Coastal management plans should be based on a detailed understanding of coastal dynamics, predictions of the shoreline positions for several spatial and temporal scenarios of climate

Figure 5. Damage in the NW coast of Portugal due to the storm of January 3-7, 2014. Examples from Matosinhos, Porto, Gaia and Furadouro (source: Público Newspaper).

variability, climate change and direct anthropogenic influencing factors, but also consider the state of vulnerability of beaches, dunes and coastal structures to storms and other extreme events, as well as the impact of these onto coastal infrastructure and environmental degradation and change (Taveira Pinto, 2004). Therefore, management plans need to be revised periodically.

Uncertainty and pressure caused by challenges of continued growth in coastal areas require new management approaches to maintain and restore the integrity and functioning of coastal ecosystems, as well as to regulate the use of land in response to ever-growing coastal risks, thereby avoiding making the same mistakes again and having to take decisions in the aftermath of coastal disasters.

As it was mentioned before, there is strong evidence that in large extensions of the NW coastal zone of Portugal, a generalized shoreline retreat is occurring causing worrisome concerns. For example, some areas are at high hazard levels from erosion, as is the case of Bonança Beach, located downdrift of the groin of Ofir. Figure 6 presenting the coastline evolution (vegetation line) at Bonança Beach, between 1965 and 2017, clearly demonstrates that persistent retreat trend.

Anthropogenic factors determine, to a greater or lesser extent, erosive patterns along the Portuguese coast. Nevertheless, a reduction of the influence of these factors in coastal ecosystems is technically possible only in a few and well identified cases and its impacts are mostly local.

Coastal risk drivers are intrinsic to natural coastal dynamics and the occurrence of physical processes that bring about relevant morphological changes, especially in coastal zones characterized by low-lying sandy beaches, such as the area under analysis. Depending on the information available, the processes usually considered are long-term erosion (in this case for the time horizons of 2050 and 2100), erosion due to the occurrence of extreme storms, erosion due to the mean sea level rise and occurrence of flooding. All processes are somehow associated to climate change (Coelho *et al*., 2009).

In this context, for defining set-back lines associated with coastal hazards for different periods of interest, it is advised to use methods based on a worst-case scenario approach, that consider shoreline evolutionary trends (basis for the initial determination of set-back lines) and changes associated with the acceleration of sea-level rise as well as the consequences

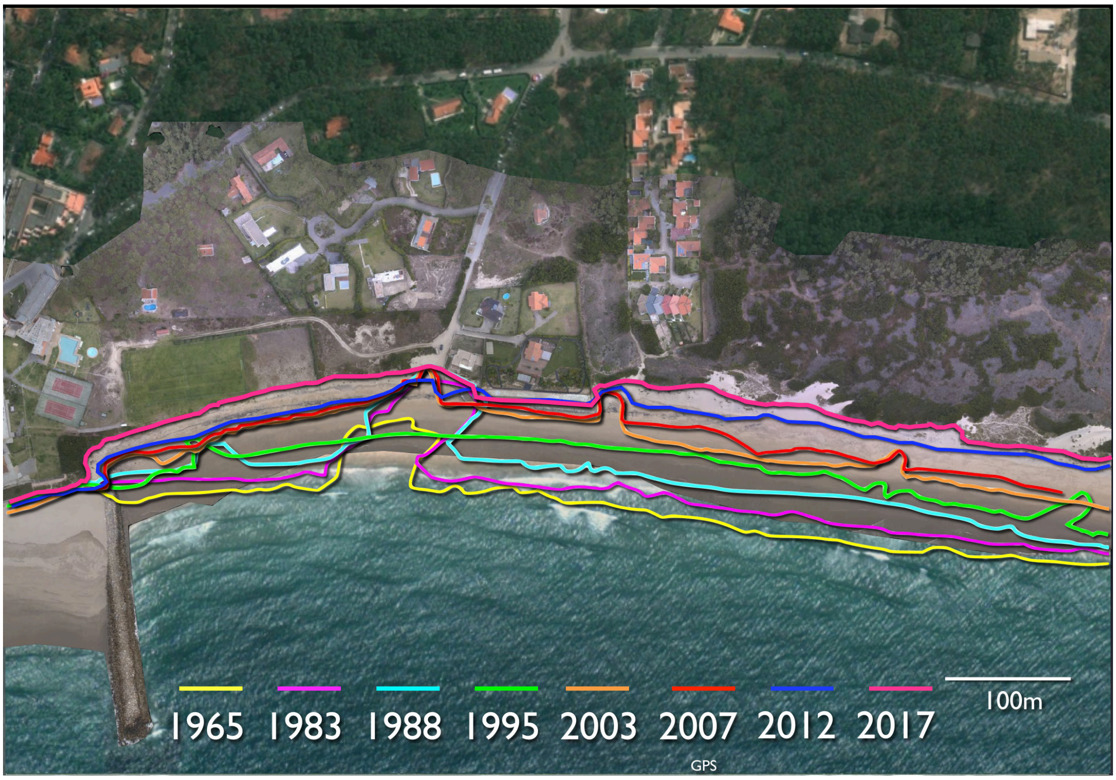

Figure 6. Coastline evolution (vegetation line) at Bonança Beach between 1965 and 2017.

of extreme storms (*e.g.*, instantaneous shoreline retreat and overwash), as the one presented in Ferreira *et al*. (2006).

In the most recent revision of *Caminha-Espinho* coastal management program of 2022, set-back lines were determined considering the vulnerability arising from the occurrence of each of the previously referred coastal processes and their expected evolution in time. Due to the high uncertainty associated to field data measurements and numerical modelling results, the definition of the set-back lines associated with each coastal process involved some expert judgment, as well as conservative principles, since the vulnerability of each coastal process and the associated set-back line may overlap. However, in this paper, only erosion trends are analyzed and briefly discussed.

The set-back lines are defined to enforce restrictions on the use and occupation of the soil, aiming at reducing projected coastal risks to 2050 and 2100, based on the extrapolation of historical coastline evolution trends. This approach has some limitations, as will be discussed in the next section.

4.2 Methodology

Coastal hazards along *Caminha-Espinho* stretch, in the northwest coast of Portugal, were assessed by comparing historical coastlines, at several years for which aerial photos were available. The retreat or the accretion rates for each profile were calculated from the changes observed in coastlines in those surveys. The final coastline evolution rate, $TELC_{(50/100)}$, was then defined assuming, for each profile and for the time horizons of 2050 and 2100, the average annual rates of shoreline change previously calculated for the *Caminha-Espinho* stretch. Then, using this rate, it is possible to project future coastline evolution, $PELC_{(50/100)}$ (erosion/accretion), as well as to define the coastline erosion set-back lines for the time horizons of 2050 (Level I, +35 years) and 2100 (Level II, +85 years). Projections are from the year 2012.

The coastline erosion set-back lines, $FSEC_{(50/100)}$, are defined as:

$$FSEC_{(50/100)} = PELC_{(50/100)} + TE_{(50/100)} + SNAM_{(50/100)} \qquad (1)$$

where $TE_{(50/100)}$ represents the direct influence of extreme storms and $SNMAM_{(50/100)}$ the direct influence of the sea level rise. The values of sea level rise considered in the assessment were +0.35 m and +1.50 m for the time horizons of 2050 and 2100, respectively.

The zone threatened by sea, $ZAM_{(50/100)}$, is defined as:

$$ZAM_{(50/100)} = TE_{(50/100)} + SNMAM_{(50/100)} \quad (2)$$

The limits of the frontal dune, represented in the field by the beach crest berm, were used as proxy for the shoreline position. When absent, the outer limit of the vegetation was used for that purpose. In general, the base of the foredune presents a more time-conservative positional nature with respect to the beach-dune border, constituting an advantage over other indicators (such as the *runup* limit and the berm crest) that are strongly influenced by daily, seasonal and interannual variations in beach morphology related to the forcing agents (*e.g.*, waves, currents, tides). The vegetation line is, usually, clearly visible in aerial photographs, providing an easily distinguishable boundary. In addition, this limit is an excellent indicator of the *runup* limit because vegetation usually disappears in flooded areas. When dune erosion buffs with a high slope are present, the limit considered was its top. In armored coastlines (*i.e.*, where seawalls, revetments, etc. are present), the limit assumed was the foot of those structures, considered as the maximum limit of potential wave run-up (Henriques, 2006).

The use of two-dimensional migration indicators, in the form of lines, is an useful approach from which straightforward information can be derived (Ferreira *et al.*, 2006). Unlike other indicators derived from the application of mathematical models, these lines effectively materialize an actual coastline change. However, this approach does not allow determining sedimentary budgets, which calculation is essentially three-dimensional. For example, this approach is not suitable to identify areas where the beach width is decreasing or where the frontal beach is eroding (as is typically the case in front of armored shorelines), even though the coastline retreat (*i.e.*, the vegetation line) is insignificant. Notwithstanding, the set-back lines have the advantage of having intrinsically incorporated factors influencing coastal dynamics locally, including storm impact, sedimentary shortages and mean sea level rise. Even though the cumulative effect of all coastline change influencing factors are present, this approach does not allow to distinguish the contribution of individual processes and thereby the hazard intensity associated with each one of them.

The coastlines used in the assessment of the rates of shoreline change were always defined using the criteria described above. The reference coastline is a coastline dated from the year 1958, provided by the Portuguese Environment Agency (APA). However, because of light overexposure in some sectors leading to a low quality of the aerial photography of 1958 for the purpose of deriving coastlines, this reference coastline does not cover the entirety of the area under analysis. The wider implication of this was that the time interval used in those sectors to compute the rates of shoreline change had to be shortened. Similarly, while some of the coastlines used in the assessment cover fully the whole area, others only partially cover it. The coastlines of 2012 and 2006, obtained from aero photographic surveys carried out for those years, fall under the former. The latter concerns the coastlines of the following years: 1948 (only for the beach of Aguçadoura North), 1965, 1973, 1983, 1987, 1994 and 1995. All imagery datasets were georeferenced using known coordinate control points, perfectly visible in the photographs and materialized in the field.

The coastline evolution trends were analyzed by quantifying its mobility, as extracted from aerial photography of different dates, with the application of the Digital Shoreline Analysis System (DSAS), developed by the USGS (Danforth *et al.*, 1992; Thieler *et al.*, 2009).

The differences in position of the coastline were measured in relation to a common baseline and using a sequence of 50 m equidistant transects, Figure 7. The common baseline, from which the transects that intersect the various coastlines were obtained, was defined as far as possible in the sea and parallel to the coastlines under analysis. Since the transects are perpendicular to that common baseline, it is ensured that the intersection of these with the different coastlines occurs as close as possible to an angle of 90°, therefore reducing the possibility of underestimating or overestimating the rates of shoreline change. A 200 m buffer was defined for all available coastlines and the obtained offshore limit was chosen as the origin of the transects. This buffer was deemed adequate considering the current trends of retreat, which are mostly erosive. Therefore, it also ensures that in future work to update this data, it will not be necessary to modify the position of the common baseline, thereby assuring that the new data is consistent with previously calculated rates of shoreline change.

The DSAS automatically calculates the intersection of the transects with the various coastlines available, resulting in the calculation of a set of statistical parameters. In this paper, the

Least Mean of Square (LMS) rate was considered. End Point Rate (EPR) was used when only two shorelines were available. The EPR is defined as the ratio of total shoreline movement (*i.e.*, the distance between the earliest and the latest measurement) and the number of elapsed years, providing a yearly rate of change. Furthermore, the rates of shoreline change were obtained using the best regression line adjusted to the retreat values determined, filtering out the effect of outliers (extremes) or residual values.

The calculated rates of change are expressed in distance of variation per year (m/year). This represents the total observed coastline displacement in the time interval under analysis. Positive values represent accretion and negative values represent erosion. In order to make a correct interpretation, one must always check which temporal instants were used at each point for the calculations, by analyzing the intersected coastlines. In some cases, a high coastline mobility (distance) is observed due to a long-time interval of analysis during which low rates of shoreline change occurred, while in other cases, this coastline mobility presents similarly high values but obtained in a shorter time interval of analysis, as a result of high rates of shoreline change.

In fact, the analysis of rates of shoreline change is strongly dependent on the time interval under analysis. Sometimes a long interval masks recurrent short-term tendencies that are more important and have been maintained over the last few years. This is particularly relevant, for example, in situations where the older coastline was inland, coastline recovery has been observed in a given time period by natural causes or due to the construction of a coastal defense intervention and, in recent years, a retreat trend is occurring. In this case, the analysis of the entire time interval will lead to accretion when, in fact, the sector has been eroding in recent years. The same holds true for the opposite case in which sectors in erosion may have changed, in recent years, to a situation of accretion resulting, for example, from the construction of coastal defense works or nourishments. All statistical data obtained for each transect was expressed numerically and graphically.

To allow a more accurate analysis, trends in rates of shoreline change have been computed for several time intervals. Firstly, those rates were calculated for the entire time interval under analysis, *i.e.* between 1958 and 2012, wherever these coastlines were available. At the same time, the rates of shoreline change were estimated for the time interval between 1994 and 2012,

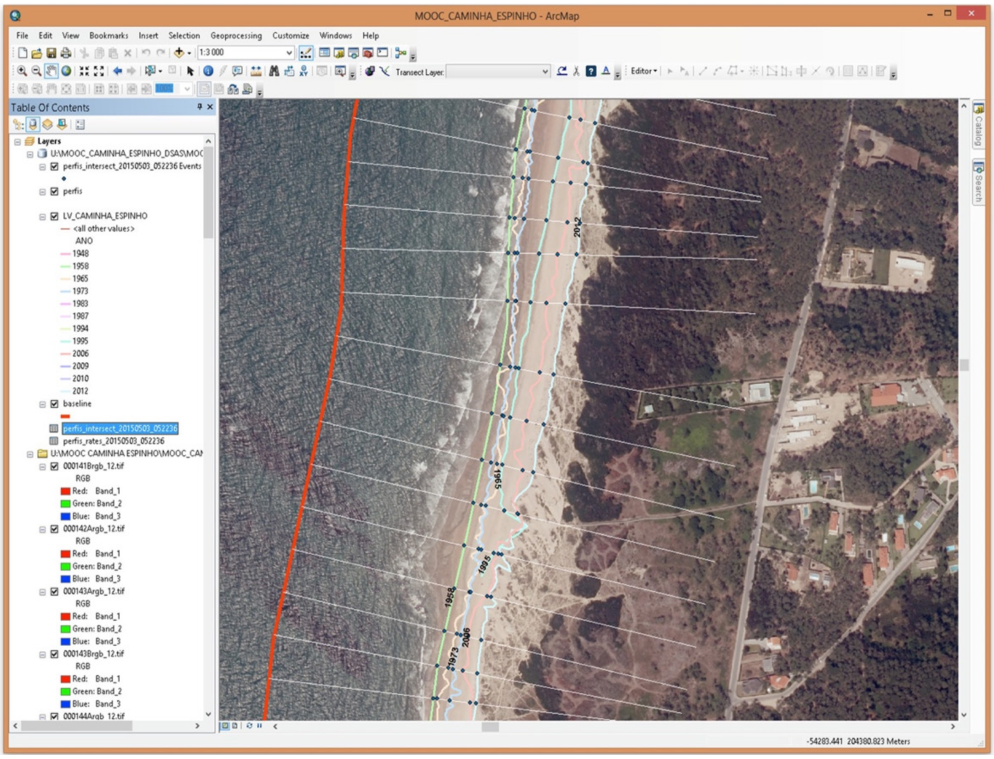

Figure 7. Example of the GIS project used to calculate the rates of shoreline change from the coastline variation, showing the intersection of the transects with the various coastlines available, which allows the calculation of the rates of shoreline change.

representing the trend in recent coastline evolution over 20 years in which information was available. Then, observed differences in the computed trends were compared, allowing a better interpretation of the past tendency to predict future evolution. For example, in some instances, there is an inversion of the evolution trend in the period from 1994 to 2012 compared to when the time interval from 1958 to 2012 is considered.

For the assessment of the overall retreat along the 120 km of the *Caminha-Espinho* coastal management program, the following sectors were analyzed:

- Mouth of Minho River (Cabedelo Beach) – Mouth of Âncora River;
- Mouth of Âncora River – Mouth of Lima River;
- Mouth of Lima River – Mouth of Neiva River;
- Mouth of Neiva River – Mouth of Cávado River;
- Mouth of Cávado River – Mouth of Ave River;
- Mouth of Ave River – Mouth of Leça River;
- Mouth of Leça River – Mouth of Douro River;
- Mouth of Douro River – Barrinha de Esmoriz.

The hazard mapping for coastal erosion considered three levels and associated thresholds: low (green) – up to 0.6 m/year; moderate (yellow) – between 0.6 and 1.3 m/year; and high (red) – above 1.3 m/year. The assessment has been carried out for both of the above-mentioned time intervals (1958-2012, and 1994-2012), any observed differences are discussed.

4.3 Results and final remarks

There is a lot of uncertainty in future coastlines predicted from the linear extrapolation of historical coastline evolution. Hence, decision-making on the long-term planning of coastal areas should cautiously and critically consider computed historical rates of change. In this paper, the average annual rates of shoreline change estimated for the overall 52/56 years (*i.e.*, $\text{TELC}_{(50/100))}$ are considered for the definition of the long-term set-back lines due to coastal erosion (Equation 1). In parallel, $\text{TELC}_{(50/100)}$ was also defined using only short-term shoreline changes for the last 20 years. The final set-back lines were established taking into account the lines obtained for these two periods. Hence, it is possible, given the uncertainty associated with long forecast intervals and using a cautious approach, to define those lines as representing a “best estimate” based on the historical coastline data available and as a “worst case scenario” in terms of local coastline evolution.

Figure 8 presents the results on rates of shoreline change for the two time periods considered, long-term and short-term, obtained for Moledo beach. It is possible to observe that in Moledo several transects show important changes in erosion hazard magnitude from the larger period of analysis to the last 20 years, being that level aggravated in recent decades (*i.e.*, between 1994 and 2012). Figure 8 also includes the coastal set-back lines for 2050 and 2100.

Because of the limited number of datasets available for the analysis, the predictions of the long-term coastline position have important limitations. The projected coastlines to the 2050 and 2100 time horizons based on observed historical trends calculated for a time interval that includes, at best, 56 years of observations is deemed high uncertainty, associated with both the mathematical approach itself and the maintenance or variance of the coastal processes influencing coastline evolution over time.

For some coastal transects, such as those in the sector from Mouth of Minho River (Cabedelo Beach) – Mouth of Âncora River (Figure 9), the integrated analysis of short- and long-term evolution trends revealed that the average of short-term changes was lower than the long-term changes (1958-2012 *versus* 1994-2012). For other profiles, the opposite behavior is observed (Figure 9).

In general, the evolution trends obtained for *Caminha-Espinho* coastal stretch agree with the ones earlier reported by Ponte Lira *et al*. (2016). The differences observed may be due to the spatial and temporal discretization used in both studies and the methodologies adopted to assess the shoreline evolution trends.

5. CONCLUSIONS

As part of the work efforts associated to the new *Caminha-Espinho* coastal management program (POC-CE), an assessment of the past shoreline changes was carried out considering historical data to derive coastline positions and determine observed erosion trends, along with the identification of the coastal areas prone to be overtopped and flooded. However, this paper intended only to present and discuss the methodology used to estimate the coastline evolution in the *Caminha-Espinho* coastal stretch, for the 2050- and 2100-time horizons. Selected results were used to show not only the potential of the applied methodology as support of coastal management plans, but also to highlight the main limitations and uncertainties when dealing with coastal erosion phenomena.

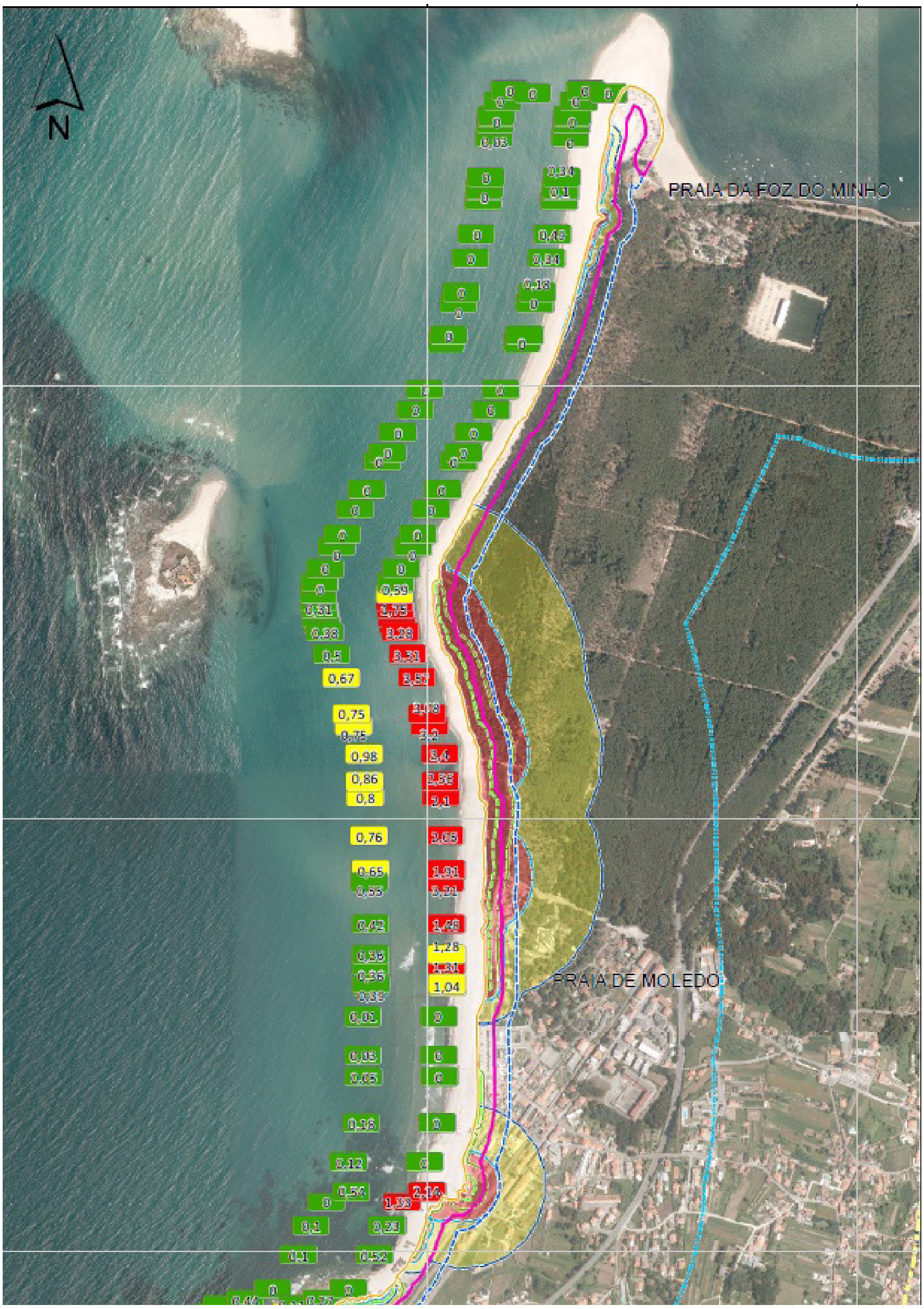

Figure 8. Analysis of Moledo beach (left squares – erosion rates 1958-2012; right squares – erosion rates 1994-2012; green – lower than 0.6 m/year, yellow – between 0.6 and 1.3 m/year, red – higher than 1.3 m/year; red area – projection for 2050; yellow area – projection for 2100).

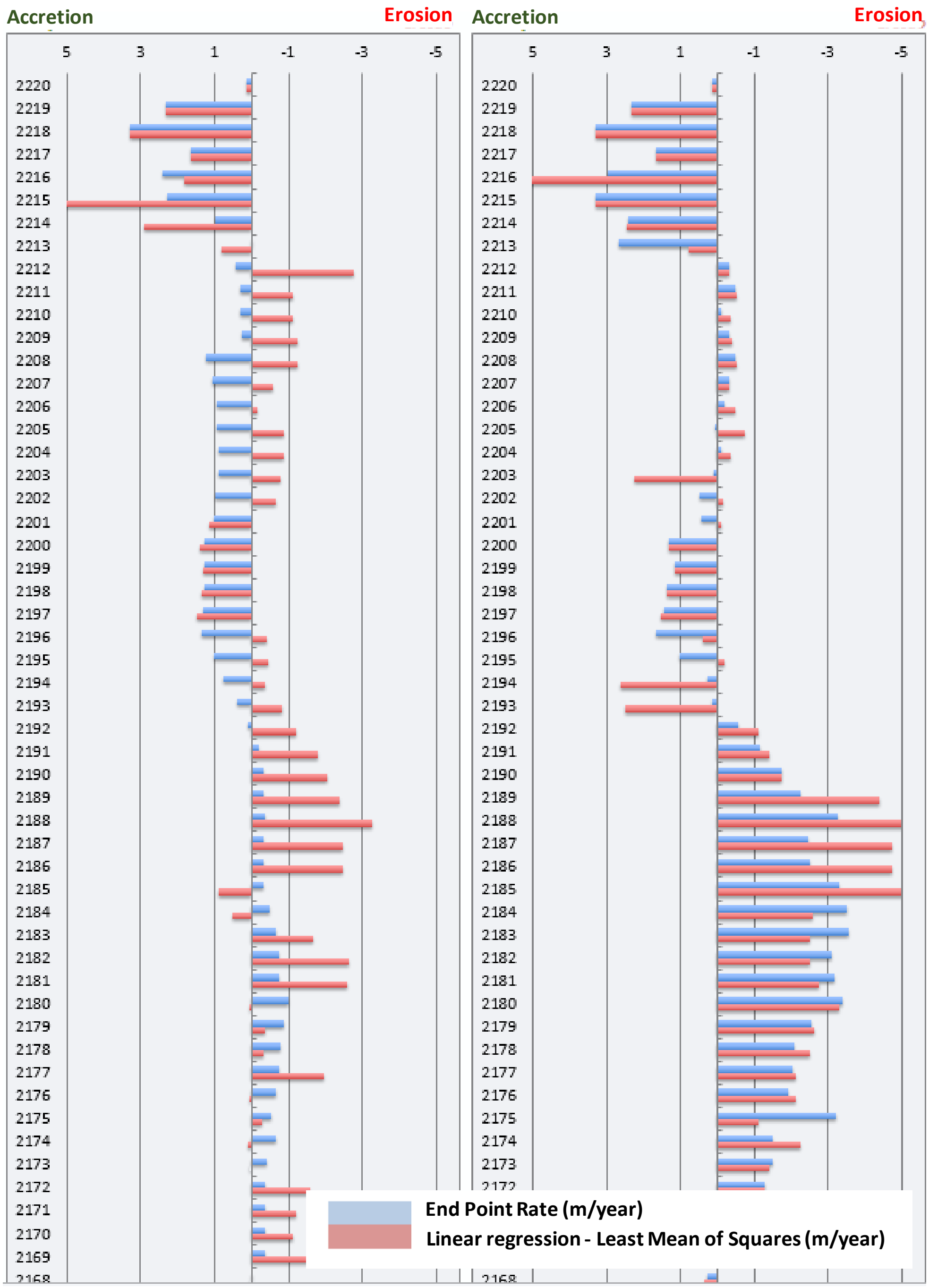

Figure 9. Example of average annual migration rates (m/year) per transect (profile) estimated for the time intervals “1958-2012” (left) and “1994-2012” (right).

The main natural and anthropogenic causes of shoreline retreat and coastal erosion on the north coast of Portugal were identified, of which insufficient sediment supply is among the most important ones. It was concluded about the importance of increasing knowledge on coastal dynamics to improve long-term predictions of coastline changes, since this knowledge is essential to establish proper management tools. To enforce consistent efforts of regulating coastal development and restoring coastal ecosystems, coastal zone management planning needs to be developed considering potential scenarios of coastline evolution – including projected effects of climate change – as well as economic growth and development, which has tremendous impact on uses and land occupation on the hinterland. The former drives the hazard components of coastal risk, whereas the latter affects exposure and vulnerability drivers. Coastline evolution patterns and trends, expressed in, *e.g.*, coastline erosion rates, are key to any coastal risk assessment because they help define areas where permanent losses of land can be expected.

The methodology used to evaluate those retreat rates for the northwest coast of Portugal, in the scope of the revision of *Caminha-Espinho* coastal management program, allowed for the evaluation of erosive trends and patterns, and thereby identify several critical areas with high coastline retreat rates, as well as areas subject to frequent overtopping/flooding events (not presented in this paper). This coastal hazard assessment considered sea level rise projections. It has shown that the Portuguese coastal ecosystems are not resilient enough to extreme events and that the Portuguese coastal zone, like very many others worldwide, will be severely affected by the effects of climate change.

Summing up, the extreme events, somehow related to climate change effects, overall need to be better characterized and their expected impacts on uses in the hinterland and coastal waters better assessed and analyzed. More specifically, risk attribution, *i.e.*, the specific contribution of each risk component (hazard, exposure, or vulnerability) to the overall risk of the coastal stretch, needs to be further considered when drafting coastal management plans because it is not enough to look only at hazard levels without taking into account uncontrolled urban expansion (risk driver for exposure) or coastal environmental degradation (both a risk driver and a consequence of poor planning). Without that analysis, coastal zone management plans will be lacking technical and scientific information and data that could help decision-makers define the best strategies to control erosion and the impact of extreme events related to climate change effects.

REFERENCES

[1] APA, 2017. Plano de ação litoral XXI. APA - Departamento do Litoral e Proteção Costeira, ARH Norte, ARH Centro, ARH Tejo e Oeste, ARH Alentejo e ARH Algarve. outubro de 2017.

[2] Bio, A., Gonçalves, J.A., Pinho, J., Vieira, L., Vieira, J., Smirnov, G., Bastos, L., 2020. Indicadores de vulnerabilidade de erosão costeira: Um estudo de caso no Norte de Portugal. Journal of Integrated Coastal Zone Management, 20(3):197-209. DOI:10.5894/rgci-n337.

[3] Bruun, P. 1962. Sea-level rise as a cause of shore erosion. Journal of Waterways and Harb. Div. 88, 117-130.

[4] CEZCM, 2020. Desafios para a Adaptação do Litoral às Alterações Climáticas. Comissão Especializada das Zonas Costeiras e do Mar. APRH – Associação Portuguesa de Recursos Hídricos. Relator: Rui Lança 23/10/2020.

[5] Coelho, C., Silva, R. Veloso-Gomes, F., Taveira-Pinto, F. 2009. Potential Effects of Climate Change on Northwest Portuguese Coastal Zones, ICES (International Council for the Exploration of the Sea), Journal of Marine Sciences, 66(7), Oxford Journals (Oxford University Press): 1497-1507 (Effects of Climate Change on the World's Oceans), ISSN 1054-3139 (doi:10.1093/icesjms/fsp132);

[6] Dean, R.G., Kriebel, D. e Walton, T. 2008. Cross-shore sediment processes. In: Walton e King (editors). Coastal Engineering Manual. Part III - Coastal sediment processes. Chapter 111-3.1110-2- 1100 USACE. Washington, DC.

[7] Danforth, W. W., and Thieler, E. R., 1992, Digital Shoreline Analysis System (DSAS) User's Guide, Version 1.0: U.S. Geological Survey Open-File Report 92-355.

[8] EC, 2000. Water Framework Directive (2000/60/EC) of the European Parliament and of the Council - establishing a framework for Community action in the field of water policy. 23 October 2000.

[9] Ferreira, Ó., Garcia, T., Matias, A., Taborda, R., and Alveirinho Dias, J. (2006). An integrated method for the determination of set-back lines for coastal erosion hazards on sandy beaches. Continental Shelf Research, 26(9), 1030-1044. https://doi.org/10.1016/j.csr.2005.12.016

[10] Henriques, R., 2006. Monitorização da zona costeira tendo em vista a sua vulnerabilidade. Aplicação à zona noroeste de Portugal. Ph.D. Thesis, Universidade do Minho, Braga, 486p.

[11] Ponte Lira, C., Nobre Silva, A., Taborda, R., and Freire de Andrade, C. (2016). Coastline evolution of Portuguese low-lying sandy coast in the last 50 years: an integrated approach. Earth System Science Data, 8, 265-278. https://doi.org/10.5194/essd-8-265-2016.

[12] Rosa-Santos, P., Veloso-Gomes, F., Taveira-Pinto, F., Silva R., Pais-Barbosa, J., 2009. "Evolution of Coastal Works in Portugal and their Interference with Local Morphodynamics". Journal of Coastal Research, SI56, pp.757-761, ISSN: 0749-0208.

[13] Nave, S., Rebêlo, L., 2022. Long-term Coastline evolution of Figueira da Foz – Nazaré sector (Portugal). Journal of Integrated Coastal Zone Management, 22 (2), pp. 145-168. ISSN 1646-8872. DOI: 10.5894/rgci-n507.

[14] Santos, F.D., Lopes, A.M., Moniz, G., Ramos, L., Taborda, R., 2017. Grupo de Trabalho do Litoral: Gestão da Zona Costeira: O desafio da mudança. ISBN: 978-989-99962-1-2.

[15] Taveira-Pinto F. 2004. The Practice of Coastal Zone Management in Portugal. Journal of Coastal Conservation, Volume 10: 1-2, December, OpulusPress, ISSN 1400-0350, pp.147-157.

[16] Taveira-Pinto, F., Rosa-Santos, P., Fazeres-Ferradosa, T. 2021a. Integrated coastal zone management: Preservation, adaptation and monitoring [Gestão integrada das zonas costeiras: Preservação, adaptação e monitorização]. Journal of Integrated Coastal Zone Management, 21 (1), pp. 5-9. DOI: 10.5894/RGCI-N442

[17] Taveira-Pinto, F., Rosa-Santos, P., Fazeres-Ferradosa, T. 2021b. Coastal dynamics and protection. Journal of Integrated Coastal Zone Management, 21 (2), pp. 69-72. DOI: 10.5894/rgci-n406.

[18] Thieler, E.R., Himmelstoss, E.A., Zichichi, J.L., and Ergul, Ayhan, 2009. Digital Shoreline Analysis System (DSAS) version 4.0 — An ArcGIS extension for calculating shoreline change: U.S. Geological Survey Open-File Report 2008-1278.

[19] Veloso-Gomes, F., Taveira-Pinto, F., Neves, L., Pais-Barbosa, J. 2006. EUrosion. A European Initiative for Sustainable Coastal Erosion Management. Pilot Site of River Douro – Cape Mondego and Case Studies of Estela, Aveiro, Caparica, Vale do Lobo and Azores, Instituto de Hidráulica e Recursos Hídricos (IHRH), Faculdade de Engenharia da Universidade do Porto (FEUP), 340 pp., ISBN 972-752-074-X.