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Revista de Gestão Costeira Integrada

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Table of Contents

Editorial Note

Articles

ASSOCIAÇÃO PORTUGUESA DOS RECURSOS HÍDRICOS
APRH

Journal of Integrated Coastal Zone Management (2022) 22(2): 99-102

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Editorial note / *Nota editorial*

COASTAL ENVIRONMENT: RISKS AND IMPACTS

Francisco Taveira-Pinto[1], Paulo Rosa-Santos[1], Tiago Fazeres-Ferradosa[1], A. Rita Carrasco[2]

Coastal regions show a varied exposure to anthropogenic and natural risks, whose impact can often endanger the delicate balance of coastal habitats. Over the past issues of the Journal of Integrated Coastal Zone Management, several coastal risks have been broadly analysed, along with practical case studies, novel research and scientific findings (*e.g*., Taveira-Pinto *et al*. (2021), Hoff *et al*. (2022) and Costa (2022)).

The continuous study of coastal risks, hazards, and the short or long-term interactions between inhabitants and the coast, remains an important research topic, particularly given the rising pressure in coastal areas, due to widely known factors, *e.g*. climate change, increasing population and development of large cities, as well as the increase of industrial, commercial and social activities near the coast (Pelling and Blackburn, 2013), including recently boosting sectors of the so-called sea economy, such as the ones related to marine renewable energy and aquaculture, among others.

In this context, the present journal issue provides a unique set of works dedicated to the analysis of several environmental risks and impacts, which represent paradigmatic cases that have a profound impact on the sustainable and integrated management of coastal resources.

Nascimento *et al*. (2022) provided a detailed analysis of the conservation units of the Brazilian Coast under oil spilling events. The paper discusses the importance of these units' definition, in order to reach efficient and adequate measures that can reduce environmental impacts arising from oil spills. The management and contingency plans associated with each of the 119 conservation units are analysed. The results show that in most of them there is a complete absence of management and contingency plans, while in the remaining portion of 42 out of 199, only 20 were in the areas affected by the oil spilling events. Such area affected 26 municipalities and 7 states. The conducted analysis showed that none of these cases had a management and contingency plan covering the chemical impacts related to oil spilling, which in turn leads to unprepared populations and authorities in case of a disaster. This study concludes with recommendations to update the management and contingency plans of coastal regions in Brazil and provides a benchmark study that can be useful for other nations and municipalities with heavy oil and maritime traffic related activities.

The presence of intense economical and industrial activities, such as the aforementioned, or the ones associated with marine energy, typically imply the deployment of equipment, assets, and infrastructures that also cause additional pressure to the local fauna and flora. A particular risk arising from the presence of these infrastructures in marine habitats is the collision with animals, such as large mammals, fishes, and birds. The development of scientific knowledge on this topic is a key step to promote the sustainable

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growth of full-scale marine renewable energy projects. Silva *et al*. (2022) highlighted the importance of defining priority species for monitoring in terms of their collision risk with marine energy harvesting technologies on the Brazilian coast. In this review, the knowledge about the collision risks with these assets and different species is reviewed and synthesized. For the studied species, the behavioral and the regional aspects influencing the collision risk are established and their importance is discussed depending on the type of species. The study covered a set of 5 species of marine mammals, 13 taxa of marine seabirds, 5 species of endangered sea turtles and 18 species or groups of species of fish of economic importance to the region of interest. The review shows that monitoring challenges exist and that these should be covered so that accurate quantification of collision risks can be made. Furthermore, it is also highlighted that monitoring of priority species and their collision risks is an important contribution to the development of marine renewable energy harvesting within a perspective that can be considered as environmentally sustainable.

In the third paper of this issue, Osorio *et al*. (2022) provided a water quality analysis based on the *Brachionus Plicatilis* (Rotifera) for the interesting case of the Callao Bay in Peru. The Callao Bay represents a rich coastal region and is the most important of the Peruvian bays and one of the most important ones in South America. Additionally, the Callao Bay is a place of intense marine economic and industrial activities and hosts the Callao Port Terminal, which concentrates 90% of Peru's maritime transport. Therefore, this case study represents a good example of a coastal region that is under different environmental risks, with the water quality decrease being a serious environmental impact. The seawater bathing the city of Callao receives drainage and discharge of industrial effluents and waste transported by the Rímac and Chillón rivers, which adds up to oils, solids and other pollutes that sum up to three times more than the amount contained in the domestic wastewater produced by the city itself (Osorio *et al*., 2022). In this study, the water samples taken from four different areas (including one near the Port's Terminal), were analysed using the *Brachionus Plicatilis* as a bio-indicator organism, and the data was explored by means of Principal Component Analysis. The paper also addresses the local coastal dynamics, in terms of the influence of the river's discharges in the bay, and the intensification of pollutants in the bay due to "El Niño"'s intense rainfall, among other aspects, concluding that *B. Plicatis* is indeed a suitable bio-indicator for the local assessment of water quality, which in this case has been shown to be under severe anthropogenic pressure and exposed to important environmental risks.

Albeit the anthropogenic pressure and the environmental impacts resulting from human activities, coastal regions are remarkably dynamic zones *per se*, both in time and space, thus meaning that extreme events, erosion and other important risks remain important aspects that contribute to the ever-changing shape of the coast and its associated environmental impacts. With this in mind, Rebêlo and Nave (2022) address the region of Figueira da Foz and provide a study on the long-term evolution of the local coastline. This Portuguese region is a particularly interesting case, due to its severe proneness to both retreat and flooding. A continuous, high-resolution, dataset on coastal evolution covering the time-lapse between 1947 and 2015 is presented. The data set was obtained within the Programme "Geological and Coastal Hazard Mapping" at a 1:3000 resolution scale, at the National Laboratory of Energy and Geology (LNEG). The relative displacements of the coastline are assessed by means of the Net Shoreline Movement index, whereas the total change is assessed by means of the Shoreline Change Envelope, both included in the DSAS geospatial tool. The study concludes that Figueira da Foz (Nazaré sector) registered a land loss of 1 164 888 m^2 during the covered period over a span of 30 470 m of the coastal fringe, whereas in the remaining 21 010 m of span a land-gain of 462 330 m^2 was observed. The present research stands as a useful example for similar studies world-wide and clearly highlights the advantage of using high-resolution spatial datasets at a regional scale to promote the accuracy of risk mitigation measures related to the erosion phenomenon.

In summary, the research compiled in this issue makes a useful set of practical evaluations of environmental risks and impacts in coastal regions, to which must be added the readings of other previously published works related to the same topic, *e.g.* as the ones gathered in Taveira-Pinto *et al*. (2021).

ZONAS COSTEIRAS: RISCOS E IMPACTES

*As zonas costeiras estão expostas a vários riscos antropogénicos e naturais, cujos impactes colocam muitas vezes em perigo o delicado equilíbrio presente nos habitats costeiros. Nos últimos números da Revista de Gestão Costeira Integrada foram analisados vários riscos costeiros, casos de estudo práticos, bem como realçadas descobertas científicas recentes sobre riscos costeiros (*p. ex.*, Taveira-Pinto et al. (2021), Hoff et al. (2022) e Costa (2022))*

O estudo continuado dos riscos costeiros, perigos na zona costeira e das interações a curto ou longo termo entre os habitantes das zonas costeiras e a costa propriamente dita, continuam a ser tópicos importantes de investigação dada a crescente pressão nas zonas costeiras e a factores amplamente conhecidos, como por exemplo, as alterações climáticas, o aumento da população e o desenvolvimento de grandes cidades, o aumento das atividades industriais, comerciais e sociais perto da linha de costa (Pelling e Blackburn, 2013), incluindo a recente alavancagem de sectores ligados à economia do mar, tais como os relacionados com a exploração das energias renováveis marinhas e a aquacultura offshore, entre outros exemplos.

Neste contexto, o presente número da revista apresenta um conjunto único de trabalhos dedicados à análise de vários riscos costeiros e impactes ambientais nas zonas costeiras, representativos de casos paradigmáticos com profunda expressão numa gestão sustentável e integrada dos recursos.

Nascimento et al. (2022) apresentam uma análise detalhada de unidades espaciais de conservação da zona costeira brasileira, sujeitas a eventos de derramamento de petróleo. O artigo discute a importância de definir estas unidades de conservação, por forma a alcançar medidas eficientes e adequadas de gestão, que possam reduzir os impactes ambientais decorrentes de derrames de petróleo. São analisados os planos de gestão e de contingência associados a cada uma das 119 unidades de conservação. Os resultados mostram que, na maioria das unidades de conservação consideradas, se verifica uma completa ausência de planos de gestão e de contingência, enquanto na minoria restante, 42 das 199, apenas 20 se encontram afetadas por eventos de derrame de petróleo. Estas últimas cobrem 26 municípios e 7 estados. A análise levada a cabo pelo autores mostrou que nenhuma destas unidades tinha um plano de gestão e contingência que abrangesse os impactes químicos relacionados com o derrame de petróleo, o que por sua vez cria populações e autoridades de gestão sem preparação técnica em caso de catástrofe. O estudo recomenda a atualização dos planos de gestão e de contingência das regiões costeiras no Brasil e afigura-se como estudo de referência, útil para outras nações e municípios com atividades relacionadas com o petróleo e o tráfego marítimo.

A presença de atividades económicas e industriais intensas, tais como as acima mencionadas, ou as associadas à exploração de energias renováveis marinhas, implicam, tipicamente, a instalação de equipamentos e infraestruturas nas zonas costeiras, com um aumento da pressão humana na fauna e flora locais. Um risco decorrente da presença destas infraestruturas em habitats marinhos é o risco de colisão com animais marinhos, tais como os grandes mamíferos, peixes e aves. O desenvolvimento do conhecimento científico sobre este tema é fundamental para promover o crescimento sustentável de projetos de energias renováveis marinhas. No estudo de Silva et al. (2022) sublinha-se a importância de se definirem espécies prioritárias para monitorização, no contexto dos riscos associados à sua colisão com infraestruturas de exploração de energia marinha na costa brasileira. Neste artigo de revisão, é sistematizado o conhecimento existente acerca dos riscos de colisão e as várias espécies afetadas. Para as espécies detalhadas no estudo, estabelecem-se os aspetos comportamentais e regionais que influenciam o risco de colisão, bem como a sua relevância em função do tipo de espécie. O estudo abrangeu um conjunto de 5 espécies de mamíferos marinhos, 13 taxa de aves marinhas, 5 espécies de tartarugas marinhas ameaçadas e 18 espécies ou grupos de espécies de peixes com interesse económico para a região. O artigo de revisão mostra que existem ainda desafios em termos de monitorização e como estes devem ser tratados para que se possa fazer uma quantificação precisa dos riscos de colisão. Por fim, salienta que a monitorização de espécies prioritárias e respetivos riscos de colisão é um contributo vital para o desenvolvimento das energias renováveis marinhas, numa perspetiva de desenvolvimento ambiental sustentável.

No terceiro artigo deste número, Osorio et al. (2022) apresentam para o interessante caso da Baía de Callao, Perú, uma análise da qualidade da água baseada no Brachionus Plicatilis (Rotifera). A Baía de Callao integra uma região costeira rica, com elevada importância no contexto das baías peruanas, e uma das mais importantes da América do Sul. A Baía de Callao é também um local de intensa atividade económica e industrial marítima e acolhe o Terminal Portuário de Callao, que concentra 90% do transporte *marítimo do Perú. Assim, o referido estudo analisa um bom exemplo de uma região costeira sujeita a variados riscos ambientais, sendo a diminuição da qualidade da água um dos principais impactes ambientais. A água do mar que banha a cidade de Callao recebe drenagem e descarga de efluentes industriais e resíduos transportados pelos rios Rímac e Chillón, que contém óleos, resíduos sólidos e outros poluentes, em quantidade três vezes superior à quantidade encontrada nas águas residuais domésticas da própria cidade (Osorio et al., 2022). Neste estudo, foram analisadas amostras de água recolhidas em quatro locais distintos (incluindo um perto do Terminal do Porto), utilizando o Brachionus Plicatilis como bio-indicador ambiental, e os resultados foram depois explorados através de uma análise de componentes principais. O artigo aborda ainda a dinâmica costeira local, em termos de influência das descargas do rio na baía, a intensificação de poluentes na baía devido à intensa precipitação do "El Niño", entre outros aspetos, concluindo que B. Plicatis é de facto um bio-indicador adequado para a avaliação da qualidade da água local, que neste caso, demonstrou estar sob forte pressão antropogénica e exposta a importantes riscos ambientais.*

Para além da pressão antropogénica e dos impactes ambientais resultantes das atividades humanas, as regiões costeiras constituem zonas extraordinariamente dinâmicas per se, tanto no tempo, como no espaço, o que significa que eventos climáticos extremos, a erosão costeira e outros riscos costeiros importantes, permanecem importantes e contribuem para a constante alteração da morfologia costeira e impactes ambientais associados. Nesta perspetiva, Rebêlo e Nave (2022) descrevem a evolução a longo termo da posição da linha de costa na região da Figueira da Foz. Esta região portuguesa é um caso particularmente interessante de dinâmica costeira, devido à sua marcada tendência para recuar e ocorrência de inundações costeiras. O estudo apresenta um conjunto contínuo de dados de alta resolução, sobre a evolução costeira entre 1947 e 2015. O conjunto de dados foi obtido no âmbito do Programa "Mapeamento do Risco Geológico e Costeiro" à escala 1:3000, do Laboratório Nacional de Energia e Geologia (LNEG). Os deslocamentos relativos da posição da linha de costa são avaliados com base no índice Net Shoreline Movement, enquanto o deslocamento resultante no período total de estudo é avaliado com base no índice Shoreline Change Envelope, ambos incluídos na ferramenta geoespacial DSAS. O estudo conclui que a Figueira da Foz (sector da Nazaré) registou uma perda total de cerca de 1 164 888 m^2 de área costeira no período em estudo, numa extensão de cerca de 30 470 m de orla costeira, enquanto que nos restantes 21 010 m de extensão foi observado um ganho de território de 462 330 m^2. A investigação levada a cabo afigura-se com um útil exemplo para outros casos de estudo a nível mundial, destacando claramente a vantagem de se utilizarem dados espaciais de alta resolução à escala regional, com o intuito de se desenvolverem medidas mais precisas de mitigação de riscos associados ao fenómeno da erosão costeira.

com base no Em resumo, os temas de investigação compilados neste número constituem um conjunto útil de avaliações práticas de risco costeiro e impactes ambientais nas regiões costeiras, a que se devem juntar outras leituras anteriores relacionadas com este tópico, como por exemplo os trabalhos reunidos em Taveira-Pinto et al. (2021).

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USE OF *BRACHIONUS PLICATILIS* (ROTIFERA) TO ASSESS THE QUALITY OF MARINE WATER IN CALLAO BAY, PERU

Marco Osorio[1], Seid Romero[1], Angélica Guabloche[1], Lorena Alvariño-Flores[1], Yuri Ayala-Sulca[2], Carlos Carrasco-Badajoz[3], Luz Castañeda[1], Luis Carrasco[4], Jose Alberto Iannacone[@ 1, 5, 6]

ABSTRACT: The present investigation used *Brachionus plicatilis* (Rotifera) to evaluate the water quality in Callao Bay, Peru. The water samples were taken in four areas: P_1 in La Punta, P_2 in Chucuito, P_3 in front of the Callao Port Terminal and P_4 in the San Lorenzo and El Frontón Islands, and in four seasonal periods: autumn-2015, winter- 2015, spring-2015, and summer-2016. Physical-chemical parameters, chlorophyll, phycocyanin, heavy metals, and bioassays with seawater at 24 h and 48 h of exposure to *Brachionus plicatilis* obtained from a standardized culture were evaluated in each area and seasonal period. High concentrations of Ag, Pb, Hg, Cu, Cr, Ni and Zn were found at all the sampling sites. The no observed effect concentration (NOEC) values (concentration at which a significant effect of mortality is not observed with respect to the control) and lowest observed effect concentration (LOEC) (minimum concentration at which a significant effect of mortality is observed with respect to the control) at 48 h of exposure to the *B. plicatilis* bioassay were lower for P_1 (winter-2015) and P_2 (winter-2015). Principal components analysis (PCA) showed that principal component 1 (PC_1) contributed 38.70% and PC_2 17.70%. PC_1 was formed by LOEC of Cd, Hg, Ni, Ag, and Pb while PC_2 was related to Cu, Cr and Zn. According to these results *Brachionus plicatilis* can be used as a bioindicator organism to assess water quality in the marine environment.

Keywords: acute bioassay, *Brachionus*, heavy metals, mortality, rotifer.

RESUMO: *A presente investigação utilizou Brachionus plicatilis (Rotifera) para avaliar a qualidade da água na Bahía del Callao, Peru. As amostras de água foram coletadas em quatro locais:* P_1 *em La Punta,* P_2 *em Chucuito,* P_3 *em frente ao Terminal Portuário de Callao e* P_4 *nas Ilhas San Lorenzo e Frontón, e em quatro períodos sazonais: outono-2015, inverno-2015, primavera-2015 e verão-2016. Os parâmetros físico-químicos, clorofila, ficocianina, metais pesados e bioensaios com água do mar às 24 he 48h de exposição com Brachionus plicatilis obtidos em cultura padronizada foram avaliados em cada área e período sazonal. Os metais Ag, Pb, Hg, Cu, Cr, Ni e Zn foram encontrados em maior concentração em todos os locais de amostragem. Os valores de NOEC (concentração onde um efeito significativo de mortalidade não é observado em relação ao controle) e LOEC (concentração mínima onde um efeito significativo de mortalidade é observado em relação ao controle) em 48 h de exposição com o bioensaio de B. plicatilis foram menores para* P_1 *(inverno-2015) e* P_2 *(inverno-2015). A técnica de Análise de Componentes Principais (ACP) mostrou que o componente principal 1 (*CP_1*) contribuiu com 38,70% e o* CP_2 *com 17,70%.* CP_1 *foi formado por LOEC, Cd, Hg, Ni, Ag e Pb.* CP_2 *relacionou as variáveis Cu, Cr e Zn. Propõe-se a utilização de Brachionus plicatilis como organismo bioindicador para avaliação da qualidade da água no meio marinho.*

Palavras-chave: *bioensaio agudo, Brachionus, metais pesados, mortalidade, rotífero.*

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1. INTRODUCTION

Accelerated industrial development brings with it lifestyle modifications and an increase in the generation of waste and emission of pollutants towards marine and freshwater aquatic systems (Jha, 2008; Escobar-Chávez *et al*., 2019; Pascual *et al*., 2019; Sotelo-Vásquez and Iannacone, 2019), causing negative effects on aquatic life and human health (Jha, 2008; Rojas-Jaimes *et al*., 2019; Panduro *et al*., 2020).

The pollution and accumulation of heavy metals in the oceans must be investigated and analyzed. The term heavy metal (HM) refers to any metallic chemical element that has a high density and is toxic at very low concentrations (Cousseau and Perrotta, 2013). HMs are dangerous because some bioaccumulate and biotransfer and because they are persistent and not destructible (Panduro *et al*., 2020). This leads to an increase in the concentrations of these chemical elements in living organisms over a period of time compared to the concentrations in an environmental matrix (Djinovic-Stojanovic, 2015).

To evaluate the quality of seawater in marine ecosystems, physicochemical parameters are usually used individually and are contrasted with an environmental quality standard, which has limitations because toxic effects to the biota are disregarded as are additive, antagonistic and synergistic interactions between contaminants (Cousseau and Perrotta, 2013; Casanova-Rosero *et al*., 2015; Planes and Fuchs, 2015).

Callao Bay, in Peru, has historically shown that the concentration of pollutants, including HM, has exceeded the environmental quality standards of the Peruvian Water Law (MINAM, 2017). Therefore, adequate effluent treatment and disposal systems must be implemented (*i.e.*, treatment plants and submarine emitters) (Larios-Meoño *et al*., 2015).

Protocols have been established to assess the environmental quality of marine ecosystems using bioindicator species (Cousseau and Perrotta, 2013; Ferrari, 2015). Toxicity bioassays are simple, practical, sensitive, and repeatable and, whenever possible use native species (Cousseau and Perrotta, 2013; Herkovits *et al*., 2015).

Among the indicator species of the aquatic environment, there are rotifers that are components of zooplankton, which are key in trophic webs and present a wide geographical distribution (Toscano and Severino, 2013; Jeong *et al*., 2019ab; Gharaei *et al*., 2020). *Brachionus* is one of the genera with more species in the Phylum and is called "the white mouse" of rotifers (Toscano and Severino, 2013; Jeong *et al*., 2019ab; Alvarado-Flores *et al*., 2019). *Brachionus plicatilis* is a species widely used in aquaculture to feed more than 60 species of bony fish larvae and 18 species of crustaceans (Sharma *et al*., 2018; Yona, 2018), in which they have been used to evaluate nutritional aspects (Ortega-Salas and Reyes-Bustamante, 2013; Rahman *et al*., 2018; Contreras-Sillero *et al*., 2019; Ferrando *et al*., 2019), reproductive (Sun *et al*., 2017; Yona, 2018), as well as developmental biology (Clark *et al*., 2012) and geographical distribution (Toscano and Severino, 2013). *B. plicatilis* is considered a complex of cryptic species with various morphotypes (Guerrero-Jiménez *et al*., 2019; López *et al*., 2019).

The rotifer *B. plicatilis* is a useful model for evaluating aquatic ecotoxicity due to its ecological relevance, biological and practical characteristics, rapid reproduction and short life cycle (Rico-Martínez *et al*., 2013). The toxic effects of particulate matter, other chemical substances and algae toxins have been evaluated using *B. plicatilis* (Rico-Martínez *et al*., 2013; Li *et al*., 2018).

The objective of this study was to perform toxicity bioassays using *B. plicatilis* to evaluate the quality of seawater in Callao Bay, Peru.

2. MATERIAL AND METHODS

2.1 Study area

The city of Callao is located in a strategic site along a long coastline receiving the cold waters of the Humboldt Current, making it the first seaport in Peru and one of the most important ports in South America. The main economic activity is manufacturing industries. Other important economic activities involve the export of frozen fish from Callao, representing 18.2% of the fish consumed in Peru and about 50% in the city of Lima, Peru and manufacturing plants for preparing frozen fish, flour, and canned and cured meats. Fishing in Callao also contributes directly to the generation of added value and employment. The Callao Port Terminal concentrates 90% of the country's maritime transport, both merchant and military, and has an urban environment made up of adjoining private land for residential and industrial use, a Naval Base and the Rímac River, as well as sports facilities on the south side of the port. The quality of the seawater in the province is affected by the reception of drainage, the discharge of industrial effluents and waste transported by the Rímac and Chillón rivers, which cause the values of HMs, thermotolerant coliforms, suspension of oils, fats, and solids to exceed national environmental quality standards according to current regulations. The sea of Callao receives approximately three times more domestic wastewater than the province produces.

The National Institute of Culture of Peru has declared San Lorenzo Island as Cultural Patrimony of the Nation with 20 archaeological monuments present on the island. San Lorenzo Island and El Frontón Island present marine biodiversity. These islands are close to Isla Palomino, which has populations of sea lions, and is part of the National Reserve of the System of "Islas Guaneras, Islotes y Puntas".

To perform the toxicity bioassays, four seasonal evaluations were carried out in Callao Bay during the fall (May 30)-2015, winter (August 22-23)-2015, spring (November 22-23) in 2015 and the summer (January 5-6) of 2016. The sampling areas were: P_1 at La Punta (Naval School) (12 ° 3'57.2-12 ° 4'47.8 "S, 77 ° 10'8.60" -77 ° 10'35.4 "W), P_2 in Chucuito (in front of IMARPE "Instituto del Mar del Perú") (12 ° 3 '34.91' -12 ° 3'57.45 "S, 77 ° 9'23.76-77 ° 9'35, 8 "W), P_3 in front of Callao Port Terminal (12 ° 1'59.52" - 12 ° 2'51.67 "S, 77 ° 9'6.1" - 77 ° 9'38.71 "W) and P_4 in the San Lorenzo Islands and the Fronton (12 ° 4 '23.6' '- 12 ° 6'34.73 "S, 77 ° 10'38.5" - 77 ° 13'7.5 "W). The sampling areas were georeferenced with a GPS and an echo sounder (GARMIN model map 4215) and spatially located on a map with the ArcGIS 10.8.1 for Desktop and ArcMAP 10.8 programs (Price, 2019).

According to the classification of coastal-marine water bodies in Peru, P_1 and P_3 were located at a site of the marine-port, industrial or sanitation activities, P_2 was in the area allocated for primary contact recreation, and P_4 was located at the site devoted to the extraction and cultivation of mollusks (MINAGRI, 2016).

Only one sample of surface water was collected from each sampling areas without replicates, and physicochemical parameters were determined *in situ* including sea surface temperature (SST) (°C), pH, electrical conductivity ($mS \cdot cm^{-1}$), salinity ($g \cdot L^{-1}$), total suspended solids (TSS) ($mg \cdot L^{-1}$), dissolved oxygen (DO) ($mg \cdot L^{-1}$), transparency (m), turbidity, phycocyanins ($\mu g \cdot mL^{-1}$), chlorophyll ($ug \cdot mL^{-1}$), oxide-reduction potential (ORP) (mV), ammonia ($mg \cdot L^{-1}$), and nitrates ($mg \cdot L^{-1}$). These parameters were evaluated with an EXO 2 multiparameter (YSI ® brand, United States). Chlorophyll and phycocyanins were measured by the Algae Torch R Fluorometric method (EIJKELKAMP® brand, Netherlands).

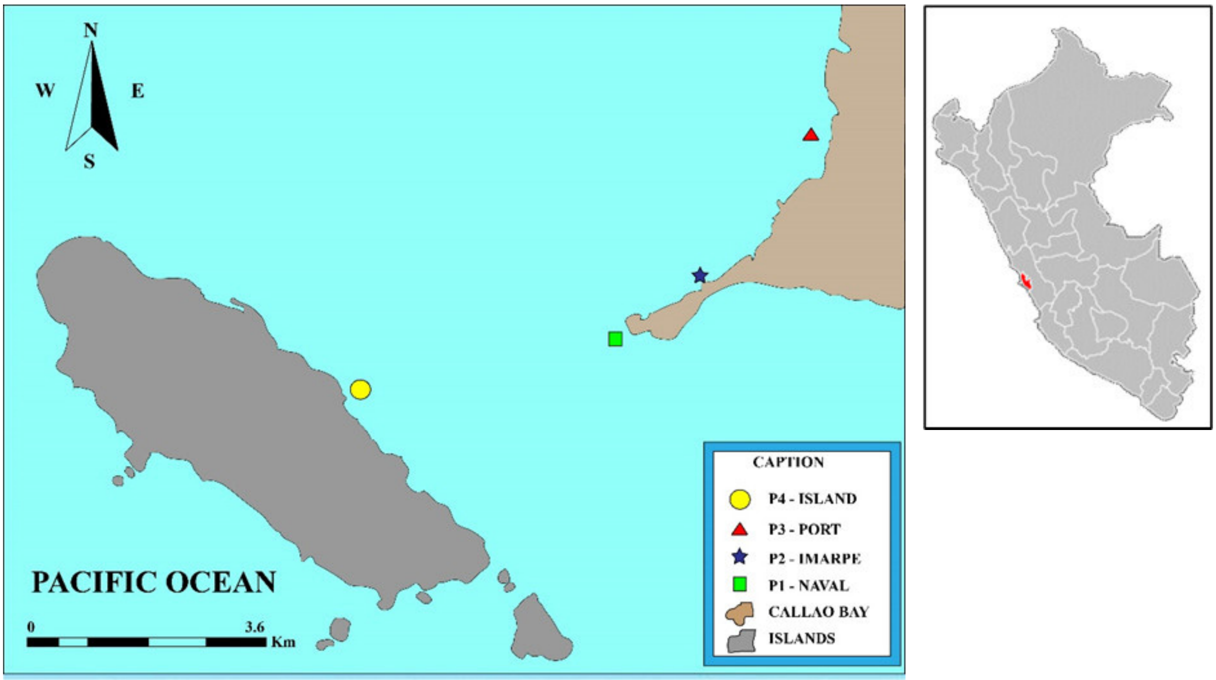

Figure 1. Sample areas in Callao Bay, Peru (ArcGIS 10.8.1 and ArcMAP 10.8). P_1 = Naval School, P_2 = in front of IMARPE, P_3 = Callao Port Terminal and P_4 = San Lorenzo and Fronton Island.

Marine water samples were taken according to standardized protocols for each of the environmental parameters evaluated (Rice *et al*., 2017). For HM analysis, 500 mL of water were collected in polyethylene containers washed and treated with nitric acid. The pH was adjusted to 2.0 with the same acid and the sample was kept at 4°C until transfer in a cooler and subsequent analysis in the laboratory, which followed quality assurance (QA) and quality control (QC) procedures to guarantee the results of the analysis of the water samples based on the Quality Management System designated by the USEPA and by the quality policy of the laboratory. QA/QC practices involve a broad range of activities including, but not limited to: a) manufacturer guidance and user manual, b) calibrations, c) acceptance, use, and maintenance of instruments and equipment, water sample chain of custody, d) pre- and post-deployment procedures, and record-keeping strategies (Rice *et al*., 2007; USEPA, 2002). The total HM content was determined by inductively coupled plasma atomic emission spectroscopy (Rice *et al*., 2017) following standard protocols (EPA 200.7, Rev 4.4, 1994) (INVEMAR, 2003; USEPA, 1994) and for Hg was determined using cold vapor atomic absorption spectrometry (Rice *et al*., 2017).

The results of the physicochemical parameters and HMs were contrasted with the National Environmental Quality Standards for Water according to Supreme Decree No-004-2017 MINAM (MINAM, 2017) and the classification of marine-coastal water bodies of Peru (MINAGRI, 2016). The HMs were also compared

Table 1. Environmental quality standards for heavy metals ($mg{\cdot}L^{-1}$) in marine water according to Peruvian and international regulations.

Metals	Peruvian standard		Canadian standard		Australian and New Zealand standard	EC Standard	USEPA		Ecuador standard
	II-C3	IV-E3	Short Term	Long Term			Acute MCC	Chronic CCC	
Sb	0.64	NA							
As	0.05	0.036		0.0125	ID	0.025*	0.069	0.036	0.05
Ba		NA							1
B	NA		GNR	GNR					5
Cd	NA	0.0088	GNR	0	0.0007	0.0002	0.0011	0.05	0.005
Cu	0.05	0.05	ND	ND	0.0003	0.025*	0.0011	0.05	0.05
Cr VI	0.05	0.05	ND	0.0015	0.00014		0.0048	0.05	0.05**
P			ND	ND					
Fe			ND	ND	ID				0.3
Mn			ND	ND					0.1
Hg	0.0018	0.0001	ND	0.000016	0.0001	0.00005	0.0018	0.00094	0.0001
Ni	0.074	0.0082	ND	ND	0.007	0.02	0.074	0.0082	0.1
Ag			0.0075	NRG	0.0008		0.0019		0.005
Pb	0.03	0.0081	ND	ND	0.0022	0.0072	0.140	0.0056	0.01
Se	NA	0.071	ND	ND			0.29	0.071	0.01
Si	NA	NA							
Tl	NA	NA							
Zn	0.12	0.081	Not evaluated	ND	0.007	0.06*	0.09	0.081	

Sb: Antimony, As: Arsenic, Ba: Barium, B: Boron, Cd: Cadmium, Cu: Copper, Cr: Chromium, P: Phosphorus, Fe: Iron, Mn: Manganese, Hg: Mercury, Ni: Nickel, Ag: Silver, Pb: Lead, Se: Selenium, Si: Silica, Tl: Thallium, Zn: Zinc. Peruvian Standard: IIC3 = Category 2: Extraction, crops and other coastal and continental marine activities. C3. Marine port, industrial or sanitation activities in coastal marine waters. IV-E3 = Category 4: Conservation of the aquatic environment. E3. Marine ecosystems. Canadian Standard Short Term and Long Term. Australian and New Zealand standard at 95% species protection. EC: European Community. * = Indicates values suggested by Tueros *et al.* (2009). USEPA: Environmental Protection Agency. MCC: Maximum Concentration Criterion, is an estimate of the highest concentration of a material in surface water that an aquatic community can be briefly exposed to without resulting in an unacceptable effect. CCC: Continuous Concentration Criterion, is an estimate of the highest concentration of a material in surface water to which an aquatic community can be exposed indefinitely without producing an unacceptable effect. Ecuador Standard: Quality Criteria of the Environmental Quality Standard and discharge of effluents to the water resource. ** = Indicates values in total Chromium. ND: No data, GNR: Guideline not recommended. ID: Insufficient data.

with five international standards: (1) the Canadian standard that indicates short-term and long-term Environmental Quality Guidelines (CCMC, 2007), (2) the Australia and New Zealand standard (ANZECC and ARMCANZ, 2000), (3) that of the European Community (EC) as indicated by Crane and Babut (2006) and Tueros (2009), (4) the standard of the United States Environmental Protection Agency (USEPA, 2009) and finally (5) that of Ecuador (AM, 2015) (Table 1).

The rotifer *B. plicatilis* was acquired from the *Universidad Científica del Sur* and from the germplasm bank of the Marine Institute of Peru (IMARPE), Lima, Peru. The culture was kept at 25°C ± 2°C in a bioclimatic chamber in continuous darkness and in 1 L Erlenmeyer flasks according to the protocol of Pérez-Legaspi and Rico-Martínez (1998). The preparation of artificial seawater for cultivation and for ecotoxicological bioassays was carried out using distilled water with 35 $g \cdot L^{-1}$ of artificial sea salt (Fluval Sea® Sal Marina, Rolf C. Hagen (USA) Corp., Mansfield, MA, USA) sterilized with ultraviolet radiation.

The experimental design for the ecotoxicological bioassays consisted of the exposure of *B. plicatilis* to seawater from each of the sampling areas in dilutions with the artificial seawater in completely randomized blocks: six concentrations or treatments with four repetitions: 100%; 50%; 25%; 12.5% and 6.25%, and a negative control; and two exposure times of 24 h and 48 h (Ferrari, 2015; Escobar-Chávez *et al*., 2019). The preparation of each concentration was carried out in 6.5 mL well plates (flat bottom 12 multi-well plates, Cole Parmer®, IL, United States). A battery of tubes was used, in which 6 mL of seawater was placed in the first tube (100%), repeated four times, then half was extracted and placed in the next tube and this was completed up to 6 mL again, and so on until the last concentration. Then, for each concentration, 10 juveniles of *B. plicatilis* from parthenogenetic females were introduced at between 0 and 24 h after birth. The temperature of the bioassays was 23 ± 1° C. Rotifers were not fed during ecotoxicological tests under dark conditions, to avoid increased swimming activity and the effect of photolysis (Snell *et al*., 1991).

The endpoint of the toxicity tests was mortality (immobility), considering individuals dead when only the presence of loric or absence of coordinated movement was evidenced when punctured with an entomological pin for 15 s under microscope observation. Based on the mortality of the rotifers, the toxicity of seawater was determined by quantifying the LC_{50} (mean lethal concentration) (Planes and Fuchs, 2015). The LC_{50} values were expressed as a percentage of dilution (volume / volume).

The general data obtained was processed in a database in EXCEL (Office, 2010). The statistical package SPSS version 20.0 for Windows 7® was used to determine the acute toxicity parameters (LC_{50} in % of the water sample). The statistical Probit model was used for each concentration of seawater and to determine the percentage of mortality (Rice *et al*., 2017) and the lower and upper 95% confidence limits at 24 h and 48 h of exposure ($p < 0.05$). In addition, the NOEC and LOEC values were obtained by means of analysis of variance (ANOVA) of a factor and a subsequent Tukey's honestly significant difference test. Before calculating the ANOVA, the Levene homogeneity of variances test and the Shapiro-Wilks normality test were performed to properly use the parametric tests (Zar,1996). Principal components analysis (PCA) was used as a data ordering and reduction technique of the number of variables employing toxicity values of LOEC of seawater with *B. plicatilis* at 48 h of exposure with eight HM from surface water in Callao Bay, Peru. HM (Cd, Cu, Cr. Hg, Ni, Ag, Pb and Zn) were selected from among those presenting Environmental Quality Standards of Canadian or European Community guidelines. The first two components were selected by PCA for the nine variables analyzed (Jolliffe and Cadima, 2016).

2.2 Ethical aspects

This study followed all the national and international ethical aspects of ecotoxicology. The use of invertebrates such as rotifers in the laboratory is allowed in ecotoxicological studies without ethical restrictions (Franco *et al*., 2014). The number of organisms used in bioassays was in accordance with the principle of the three "r's" (Oliveira and Goldim, 2014). For proper management of rotifer culture, reagents and seawater samples, as well as their disposal, the "Safety Plan for Laboratories and Workshops (SSST-PLC-01)" was followed the Rectoral Resolution No. 10026-2009 -UNFV and the "Security Protocol for Engineering, Architecture and Natural Sciences Laboratories and Workshops (SSST-PS-02)". The respective national permits were obtained from the competent national authority for collecting the water samples in Callao Bay.

3. RESULTS

Table 2 shows the variations of the physicochemical and phycocyanin and chlorophyll parameters in the four sampling areas and for the four seasonal evaluations in Callao Bay, Peru. The average SST ranged from 19.5 to 21.5°C for the areas sampled. The sequence from lowest to highest pH in the sampling areas was: $P_2 > P_3 > P_1 > P_4$. The highest values for the mean OD and for the mean transparency were for the P_4 sampling area. Phycocyanin and chlorophyll values were low in all evaluations. The highest phycocyanin and chlorophyll values were found in P_3, while the highest NH_3 levels were obtained in P_4 and for P_1.

The HMs and Ag, Pb, Hg, Cu, Cr, Ni and Zn concentrations that did not meet the water quality standards of Callao Bay, for at least some of the comparison standards and mainly for the Canadian and Australia-New Zealand regulations, were found in higher concentrations in the P_1, P_2 and P_3 sampling sites (Table 3).

Table 2. Variations of the physicochemical parameters of marine water in the sampling areas and in the station evaluations in Callao Bay, Peru.

Sampling area	Seasonal assessments	T° (°C)	pH	Cond. ($ms \cdot cm^{-1}$)	Sal ($g \cdot L^{-1}$)	TSS ($mg \cdot L^{-1}$)	DO ($mg \cdot L^{-1}$)	Transp. (m)	Turb (FTU)	Phyco ($ug \cdot L^{-1}$)	Chlorof ($ug \cdot L^{-1}$)	ORP (mV)	NH_4 ($mg \cdot L^{-1}$)	NH_3 ($mg \cdot L^{-1}$)	NO_3 ($mg \cdot L^{-1}$)
P_1	1	21.5	8.1	53.4	35.1	38142	2.49	0.86	2.4	0,1	0.30	ND	ND	ND	ND
	2	18.1	7.9	53.7	35.5	34203	2.28	0.75	4.0	0	1.40	241.3	52.38	0.32	77.88
	3	20.8	8.5	53.8	35.3	33737	1.72	5.00	0.7	0	0	184.4	60.04	2.50	2105.56
	4	21.5	8.7	53.1	34.7	34000	2.15	1.25	1.0	0	0.09	178	52.65	1.81	417.42
	Mean	20.5	8.3	53.5	35.1	35020.5	2.16	1.97	2.0	0,025	0.45	201.2	55.02	1.54	866.95
	SD	1.6	0.3	0.32	0.34	2089.73	0.33	2.03	1.5	0,05	0.65	34.85	4.35	1.11	1086.02
P_2	1	20.4	7.9	53.7	35.2	38357	1.35	3.12	2.3	0	0.20	ND	ND	ND	ND
	2	16.9	8.0	53.9	35.1	34773	2.21	2.75	2.7	0	1.60	225.3	55.43	0.30	73.98
	3	20.1	8.1	53.0	34.8	33808	0.90	2.25	7.0	0	0.68	182.7	54.89	4.25	957.67
	4	20.8	8.1	53.2	34.8	34010	1.33	3.75	2.0	0	0	176.0	51.39	1.35	365.58
	Mean	19.6	8.0	53.4	34.9	35237	1.45	2.97	3.5	0	0.62	194.6	53.90	1.97	465.74
	SD	1.7	0.1	0.42	0.21	2121.11	0.55	0.63	2.3	0	0.71	26.7	2.19	2.05	450.28
P_3	1	20.1	8.0	53.8	35.2	38428	1.74	2.87	2.9	0	0.70	ND	ND	ND	ND
	2	17.2	8.0	53.7	34.9	34180	1.44	3.00	7.6	0	1.1	211.2	64.52	0.45	156.22
	3	19.6	8.2	53.5	34.9	33893	0.89	3.00	2.5	0	0.88	176.2	54.61	3.77	672.19
	4	21.2	8.2	53.4	35.3	34076	0.65	2.25	0.7	0	0	170.9	50.22	1.26	321.85
	Mean	19.5	8.1	53.6	35.0	35144.25	1.18	2.78	3.4	0	0.67	186.1	56.45	1.83	383.42
	SD	1.6	0.1	0.18	0.21	2192.38	0.50	0,36	2.9	0	0.48	21.9	7.33	1.73	263.44
P_4	1	24.6	8.2	53.9	35.0	38500	3.61	7,50	ND	ND	ND	ND	ND	ND	ND
	2	18.4	8.1	53.7	35.1	34702	3.11	4,75	2.4	0	2	234.4	33.57	0.29	114.75
	3	19.9	8.6	53.3	34.9	34011	2.40	5,00	ND	0	0.48	170.8	53.71	4.42	562.84
	4	23.0	9.1	53.6	35.3	34104	4.32	2,75	ND	0	0	164.0	48.37	2.20	304.01
	Mean	21.5	8.5	53.6	35.0	35329.25	3.36	5,00	2.4	0	0.83	189.7	45.22	2.30	327.20
	SD	2.8	0.4	0.25	0.17	2135.89	0.81	1,95	0	0	1.04	3.8	10.43	2.07	224.94
Peruvian Standard	II-C3	Δ3	6.8-8.5			70	≥2.5								NA
	IV-E3	Δ3	6.8-8.5	NA		≤30	≥4.0								200

T° = Sea surface temperature. pH = acidity of the medium. Cond = Electrical conductivity. Salt = Salinity. TSS = Total Dissolved Solids. DO = Dissolved oxygen. Transp = Transparency. Turbi = Turbidity. Phyco = Phycocyanins. Chlorof = Chlorophyll. ORP = Oxide reduction potential. NH_4 = Ammonium. NH_3 = Ammonia. NO_3 = Nitrates. SD = Standard deviation. ND = Not determined. P_1 = Naval School. P_2 = IMARPE (Institute of the Sea of Peru). P_3 = Callao Port Terminal and P_4 = San Lorenzo Island. 1 = Fall-2015, 2 = Winter-2015, 3 = Spring-2015, 4 = Summer-2016. Peruvian Environmental Standard SQA (MINAM, 2017): Category 2: Extraction, cultivation and other coastal and continental marine activities. C3. Marine port, industrial or sanitation activities in coastal marine waters. Category 4: Conservation of the aquatic environment. E3. Marine ecosystems.

Table 3. Heavy metals (mg·L[-1]) in seawater in the sampling areas in Callao Bay, Peru.

Metals	Detection limits	Callao bay, Peru															
		1				2				3				4			
		$1P_1$	$1P_2$	$1P_3$	$1P_4$	$2P_1$	$2P_2$	$2P_3$	$2P_4$	$3P_1$	$3P_2$	$3P_3$	$3P_4$	$4P_1$	$4P_2$	$4P_3$	$4P_4$
Sb	0.006	0.01	<0.006	<0.006	<0.006	0.017	<0.006	0.020	0.032	0.01	0.022	0.025	0.016	0.023	<0.006	0.010	0.0007
As	0.0092	<0.0092	<0.0092	<0.0092	<0.0092	<0.0092	<0.0092	<0.0092	0.0283	<0.0092	<0.0092	<0.0092	<0.0092	<0.0092	<0.0092	<0.0092	<0.0092
Ba	0.0013	0.0090	0.0067	0.0059	0.0071	0.0097	0.0052	0.0066	0.0053	0.0062	0.0074	0.0069	0.0056	0.0069	0.0067	0.0079	0.0047
B	0.0016	4.25	4.22	4.34	4.31	4.34	4.33	4.30	4.33	5.24	5.82	5.11	5.70	5.11	5.09	5.32	5.91
Cd	0.0015	<0.0015	<0.0015	<0.0015	<0.0015	<0.0015	<0.0015	<0.0015	<0.0015	***0.0024***	***0.0026***	***0.0015***	***0.0036***	***0.0031***	***0.0028***	<0.0015	0.0028
Cu	0.0014	0.0067	0.0150	0.0040	0.0100	0.0058	0.0038	0.0042	0.0031	0.0105	0.0087	0.0072	0.0112	0.0067	0.0037	0.0089	0.0069
Cr	0.0016	0.0020	0.0033	0.0022	0.0220	0.0027	0.0036	0.0016	0.0016	0.0032	0.0082	0.0018	0.0053	0.0062	0.0066	0.0071	0.0049
P	0.0243	0.0890	0.1264	0.1031	0.2700	0.1308	0.1165	0.0947	0.0893	0.1684	0.1554	0.1493	0.0596	0.2716	0.1956	0.2412	0.1041
Fe	0.0083	0.2224	0.1175	0.0679	0.2000	0.1483	0.0352	0.0793	0.0108	0.06	0.1429	0.1645	0.021	0.2012	0.1422	0.1595	0.065
Mn	0.001	0.011	0.002	0.002	0.010	0.002	<0.001	0.001	<0.001	0.006	0.005	0.008	0.002	0.007	0.003	0.006	0.009
Hg	0.0001	<0.0001	***0.0004***	***0.0006***	<0.0001	***0.0007***	***0.0009***	***0.0008***	***0.0002***	<0.0001	***0.0001***	<0.0001	<0.0001	***0.0001***	***0.0001***	***0.0002***	<0.0001
Ni	0.0046	0.0115	0.0095	***0.0224***	0.0200	0.0057	0.0171	0.0091	0.0098	***0.0237***	***0.0301***	***0.0331***	***0.0304***	***0.0204***	***0.0219***	0.0185	0.0198
Ag	0.001	0.0010	<0.001	0.0020	<0.001	0.003	<0.001	0.002	0.003	0.005	0.006	0.003	0.004	0.002	0.004	0.003	0.005
Pb	0.004	***0.026***	***0.042***	***0.029***	***0.030***	***0.03***	***0.012***	***0.059***	***0.034***	***0.042***	***0.081***	***0.024***	***0.043***	***0.029***	***0.071***	***0.076***	***0.055***
Se	0.01	<0.010	<0.010	<0.010	<0.010	<0.01	<0.01	<0.01	<0.01	0.05	0.06	0.02	0.08	0.03	0.02	0.04	0.05
Si	0.0202	1.5580	1.2040	0.9301	1.1500	0.9607	1195	1335	0.6665	1.239	2.126	1.54	1.01	1.146	1.066	1.393	0.9925
Tl	0.0009	0.015	<0.015	<0.015	<0.015	0.020	<0.015	<0.0009	<0.0009	<0.0009	<0.0009	0.011	<0.0009	0.0037	0.0015	0.0016	<0.0009
Zn	0.0075	0.0164	0.0192	0.0090	0,01	0,0127	0.0113	0.0118	0.0082	0.0107	0,0122	0,0223	0.0104	0.0113	***0.0823***	0.0191	***0.1741***

Sb: Antimony, As: Arsenic, Ba: Barium, B: Boron, Cd: Cadmium, Cu: Copper, Cr: Chromium, P: Phosphorus, Fe: Iron, Mn: Manganese, Hg: Mercury, Ni: Nickel, Ag: Silver, Pb: Lead, Se: Selenium, Si: Silica, Tl: Thallium, Zn: Zinc. 1 = autumn-2015 season, 2 = winter-2015 season, 3 = spring-2015 season and 4 = summer-2016 season. P_1 = Naval School, P_2 = IMARPE (Peruvian Sea Institute), P_3 = Callao Port Terminal, P_4 = San Lorenzo Island. Numbers in bold identify values higher than the Canadian guidelines and numbers in italics indicate values above European Community guidelines.

As shown in Table 4, in the 16 toxicity bioassays with *B. plicatilis* performed after 24 h of exposure, it was observed that 93.75% (n=15) of the LC_{50} values were higher than 100%, while after 48 h of exposure, 62.5% (n = 10) of the LC_{50} values were higher than 100%.

Table 4. Marine water toxicity in Callao Bay, Peru based on LC_{50}, NOEC and LOEC on the mortality of *Brachionus plicatilis* (Rotifera) at 24 and 48 h of exposure.

Sampling	Exposure time (h)	LC_{50}	LC_{50}-lower	LC_{50}-higher	NOEC	LOEC	F	Sig
$1P_1$	24	>100	89.95	>100	12.5	25	3.11	0.04
	48	>100	99.66	>100	12.5	25	2.93	0.04
$1P_2$	24	>100	>100	>100	12.5	25	3.42	0.03
	48	70.17	32.05	>100	12.5	25	3.85	0.02
$1P_3$	24	>100	>100	>100	100	>100	2.33	0.09
	48	>100	>100	>100	50	100	2.07	0.12
$1P_4$	24	>100	>100	>100	50	100	1.87	1.53
	48	61.36	30.23	>100	12.5	25	7.80	0.00
$2P_1$	24	88.38	34.36	>100	6.25	12.5	14.28	0.00
	48	47.67	23.79	95,53	0	6.25	20.00	0.00
$2P_2$	24	>100	97.64	>100	25	50	4.09	0.02
	48	>100	18.39	>100	0	6.25	17.06	0.00
$2P_3$	24	>100	74.39	>100	6.25	12.5	16.41	0.00
	48	93.59	43.13	>100	25	50	7.96	0.00
$2P_4$	24	>100	>100	>100	50	100	1.93	0.14
	48	>100	61.19	>100	6.25	12.5	14.34	0.00
$3P_1$	24	>100	79.57	>100	6.25	12.5	6.05	0.00
	48	>100	74.88	>100	6.25	12.5	4.97	0.01
$3P_2$	24	>100	>100	>100	100	>100	1,55	0.23
	48	84.87	33.91	>100	25	50	4.14	0.02
$3P_3$	24	>100	>100	>100	6.25	12.5	7.09	0.00
	48	>100	>100	>100	100	>100	1.42	0.27
$3P_4$	24	>100	>100	>100	25	50	3.54	0.24
	48	>100	99.60	>100	50	100	3.00	0.04
$4P_1$	24	>100	>100	>100	100	>100	0.79	0.56
	48	>100	>100	>100	50	100	2.10	0.14
$4P_2$	24	>100	>100	>100	100	>100	0.91	0.50
	48	>100	>100	>100	100	>100	1.00	0.44
$4P_3$	24	>100	47.35	>100	6.25	12.5	33.39	0.00
	48	87.13	46.30	>100	6.25	12.5	24.76	0.00
$4P_4$	24	>100	99.19	>100	50	100	3.03	0.04
	48	>100	>100	>100	50	100	1.60	0.22

LC_{50} = Medium lethal concentration. LC_{50}-lower = Lower mean lethal concentration. LC_{50}-upper = Upper mean lethal concentration. NOEC = Concentration at which no significant effect is observed based on mortality with respect to the control. LOEC = Minimum concentration at which a significant effect is observed based on mortality with respect to the control. F = value of the Fisher statistic of ANOVA to calculate the NOEC and LOEC. sig = significance. Values in bold were less than or equal to 100%.

1 = autumn-2015 season, 2 = winter-2015 season, 3 = spring-2015 season, 4 = summer-2016 season. P_1 = Naval School, P_2 = IMARPE (Peruvian Marine Institute), P_3 = Callao Port Terminal and P_4 = San Lorenzo Island. h = hours.

NOEC and LOEC values were lower at 48 h of exposure in the P_1 and P_2 sampling sites in winter-2015 (Table 4). At 24 h of exposure, the following LOEC values were observed: 12.5% in four samples (25%), 25% in three samples (18.75%), 50% in two samples (12.5%), 100% and 25% in three samples (18.75%), and higher than 100% of marine waters in four samples. On the other hand, while, at 48 h of exposure, LOEC values were seen in two samples (12.5%) presented values of 6.25, three samples (18.75%) with 12.5%, three samples (18.75%) with 25%, two samples (12.5%) with 50%, five samples (31.25%) with 100% and, 12.5% higher than 100% of marine waters (two samples) (Table 4).

PCA showed that principal component 1 (PC_1) contributed 38.70% and PC_2 17.70%. PC_1 was formed by LOEC, Cd, Hg, Ni, Ag and Pb, while PC_2 was made up of Cu, Cr and Zn (Fig. 2).

4. DISCUSSION

The sampling sites P_1, P_2, P_3 and P_4 showed higher concentrations of HMs, especially Cd, Cu, Cr, Hg, Ni, Ag, Pb, Se and Zn, that did not meet the quality standards in Callao Bay water for at least some of the comparison standards and mainly for Canadian regulations and EC guidelines. High HM concentrations have been recorded in association with industrial and domestic discharges detected in Callao Bay, Peru (OECD, 2016). Three main sources of contamination have been identified in the Callao area: (1) waters of the Rímac and Chillón rivers, mainly due to the intense mining activity in the Andean zone of the valleys of these two rivers which have low salinity, high nutrient content, low DO content and high HM concentrations, (2) waters of the interior of the port, with contamination by port activities, industrial waste and the fishing terminal with high HM concentrations, and (3) area in front of the dock contaminated by the discharge of waste from ships, oil spills and periodic discharges from bars and restaurants (Guillén *et al.*, 1978).

At 48 h of exposure, 87.5% of LOEC values were observed to less than or equal to 100%, with HMs such as Cu, Cr, Hg and Zn exceeding some of the international standards for comparison (Table 1). Similarly, the DO evidenced hypoxia levels (2.28 $mg \cdot L^{-1}$) in $3P_1$ sampling area, the lowest transparency values (0.75 m) and the highest salinity value (35.5 $g \cdot L^{-1}$). The literature shows that salinity and dissolved organic matter can also influence the toxicity of Cu and other HMs, which could be explained by the binding sites available for free Cu complexes in water, forming colloids induced by salts (Kovalenko *et al.*, 2020;

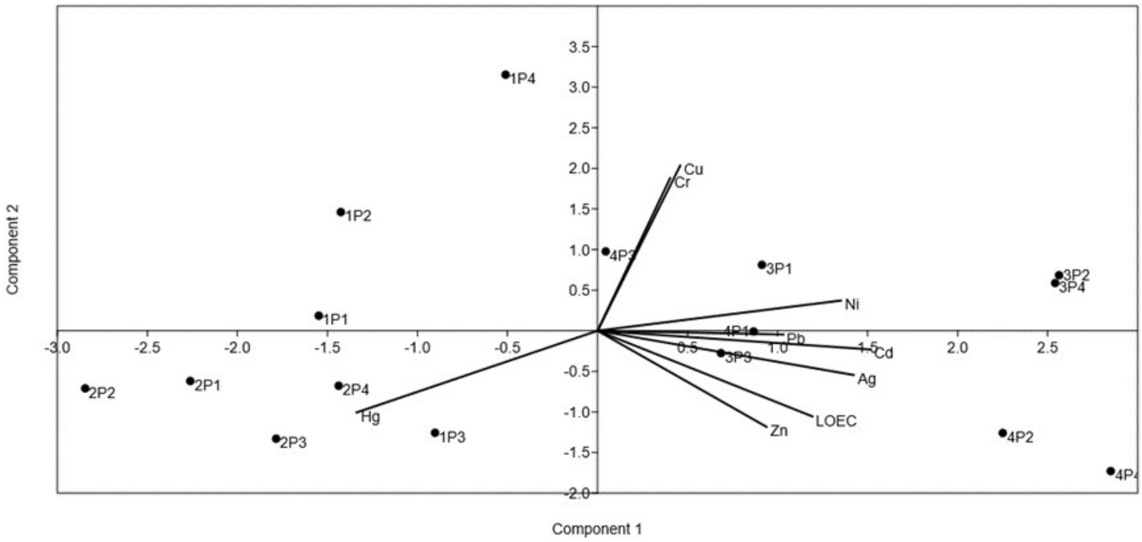

Figure 2. Principal component analysis (PCA) graph of LOEC values at 48 h of exposure with *Brachionus plicatilis* assay and heavy metals in the marine water of Callao Bay, Peru.

LOEC = Minimum concentration at which a significant effect is observed based on mortality with respect to the control. 1 = autumn-2015 season, 2 = winter-2015 season, 3 = spring-2015 season, 4 = summer-2016 season. P_1 = Naval School, P_2 = IMARPE (Peruvian Marine Institute), P_3 = Callao Port Terminal and P_4 = San Lorenzo Island.

Li *et al*., 2020). Nevertheless, more studies with the rotifer *B. plicatilis* are required to evaluate the absorption, distribution, metabolism, and excretion pathways of xenobiotics, such as many HMs, by this marine species that are determinant and essential for their toxicity (Hwang *et al*., 2016; Jeong *et al*., 2019ab; Varea *et al*., 2020). It has been reported that in other components of marine zooplankton, such as the copepods *Acartia tonsa*, *Acartia hudsonicaque*, *Notodiaptomus conifer* and *Centropages ponticus*, Cr, Hg and Cd cause changes in the egg production rate, hatching success and survival of nauplii under natural conditions and in the presence of these contaminating HMs (Hussain *et al*., 2020).

The PC_1 related Cd, Hg, Ni, Ag, Pb and LOEC. These results show that based on the LOEC, *B. plicatilis* is a suitable species to evaluate the presence of these HMs in seawater samples since a relationship was found between the LOEC of this marine rotifer and the concentrations of these HMs. The ecotoxic mortality observed based on the LOEC values could be due to a mixing effect of several chemical HM substances and not only one HM (Fu *et al*., 2014). Jeong *et al*. (2019a) showed that the marine rotifer *in vivo* exposure of *Brachionus koreanus* to a seawater sample collected from a polluted region in South Korea was not acutely toxic to adult rotifers, but both fecundity and lifespan were reduced in a concentration-dependent manner. This suggests that the main toxicity of the field-collected seawater is likely associated with Zn toxicity as well as contamination with a variety of metals. Jeong *et al*. (2019b) investigated the adverse effects of contaminated natural sea water of Youngil Bay, South Korea. This bay has shown pollution by metals due to industrial discharges from nearby steel industry complexes in seawater samples with the marine rotifer *B. koreanus*, which presented decreased population growth rates. On the other hand, no significant effects were shown in the reproduction rate or life span. Li *et al*. (2020) suggested that the rotifer *B. plicatilis* is an ideal species for use in marine ecotoxicological evaluations contaminated with HM, and reported that toxicity is higher when HMs are combined or mixed. Therefore, this rotifer is an attractive organism for these studies due to its wide distribution, ease of culture, adequate size, short generation time, and complex life cycle (Hwang *et al*., 2016; Li *et al*., 2020). However, there are very few studies on the effect of toxic metals on marine zooplankton (Hussain *et al*., 2020).

5. CONCLUSIONS

The variations in the results of HM in the bioassays with *B. plicatilis* in the different sampling areas and seasonal periods demonstrate the various industrial, recreational, transport and sports activities carried out in the coastal marine area of Callao bay. This area is one of the main localities on the Peruvian coast with marine pollution by HMs such as Cd, Cu, Cr, Hg, Ni, Ag, Pb, Se and Zn, main source of which is the wastewater of domestic, agricultural and industrial origin from the Rímac and Chillon rivers. The flow of these rivers is greater in the summer months as a result of the rains in the mountains of the province of Lima that are discharged into the sea through collectors, rivers and ditches that contribute these HMs. The activities of maritime transport and boat moorings stay of boats of different lengths of time and use also contribute HMs such as Cu, Ni and Zn. The current system in front of Callao Bay influences the movement of the HM between the different evaluation areas, and is mainly influenced by the Peruvian Coastal Current that flows in a northerly direction (Orozco *et al*., 1998; Argüelles *et al*., 2012). Among HMs, Cu is used commercially as an algaecide in antifouling paints, and Cr is used in a variety of industries as a tanning agent for leather, in electrolytic coatings of metals (electroplating), and in the production of glass, pigments, fungicides and batteries (Hussain *et al*., 2020).

The evaluation of the presence of HMs based on the different seasons, it was seen that the winter of 2015 presented the highest toxicity values based on the LOEC at 48 h of exposure compared to the summer of 2016. When evaluated by sampling areas, the P_1, and P_2 sampling areas showed a greater number of toxicity values based on LOEC at 48 h of exposure compared to points P_3 and P_4. High NH_3 values were observed in the case of P_2-spring-2015, P_3-spring-2015 and P_4- spring-2015. One study suggested that high NH_3 values significantly reduce the shelf life and egg production of *B. plicatilis* (Li *et al*., 2020). Other authors have described that the season of the year does not directly influence the toxicity of HMs. Marine waters from different geographic locations, sources of pollution and HM levels have shown lethal and sublethal toxic effects in bioassays with marine invertebrates (Beiras *et al*., 2001; Fathallah *et al*., 2011).

Reproduction and ingestion endpoints for the marine rotifer *Proales similis* were found to be generally more sensitive to HMs such as Cu, Cd, and Hg compared to hatching mortality or egg diapause (Snell *et al*., 2019). Li *et al*. (2020) reported that investigations with *B. plicatilis* could use, in addition to mortality, other biomarkers, such as behavior, enzymatic activity or gene expression, including genetic methods such as transcriptomics, with a high potential application to detect key molecular mechanisms.

The occurrence of the phenomenon of the "Niño" between the summer of 2015-2016 (ENFEN 2015), coincided with the seasons in which the water samples were collected. During this climatic phenomenon the surface temperature of the sea during the study period was 18.1 °C (16.5 to 19.9) with a thermal anomaly of 2.4 °C (1.7 to 3.5). The average annual rainfall was also exceeded by 608 mm with a maximum flow of 134.8 $m^3 \cdot s^{-1}$ in the upper part of the Rímac River. In relation to the upper part of the Chillón River, the average annual rainfall was exceeded by 506 mm with a maximum flow of 84.9 $m^3 \cdot s^{-1}$, intensifying the presence of pollutants due to the dragging of substances (discharges from the city, fertilizers, mining activity, electronic equipment or paints, etc.).

The use of *B. plicatilis* in marine ecotoxicological tests is recommended as a tool for the evaluation of environmental risks, produced by HMs and/or various pollutants, because its use in bioassays is reliable, replicable, sensitive and short in duration. In addition, it has greater ecological precision compared to other bioassays.

AUTHOR CONTRIBUTIONS

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DERRAMAMENTO DE ÓLEO NA ZONA COSTEIRA DO BRASIL: UMA ANÁLISE DAS UNIDADES DE CONSERVAÇÃO MARINHAS

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RESUMO: A implementação de mecanismos de gestão de Unidades de Conservação (UCs) e de áreas costeiras, de maneira integrada, são fundamentais nos processos de previsão de impactos e desastres, e na criação de medidas de mitigação. As zonas costeiras estão sujeitas a uma vulnerabilidade ambiental quanto a mudanças climáticas, pressões antrópicas e acidentes químicos em diferentes escalas. Dessa forma, o presente trabalho tem como objetivo analisar os planos de manejo das UCs Marinhas atingidas pelo derramamento de óleo na zona costeira do Brasil no ano de 2019, tendo em vista a verificação e análise da presença de planos de contingenciamento, bem como a identificação de possíveis ações propostas para mitigação do referido impacto. Com esta pesquisa, pôde-se constatar que das 119 UCs Marinhas nos estados atingidos, apenas 42 apresentaram plano de manejo. Destas, 20 faziam parte da área atingida pelos derramamentos, abrangendo 26 municípios em 7 estados, porém, nenhuma delas apresentou em seu plano de manejo ações referentes ao contingenciamento ou mitigação de impactos devidos a acidentes químicos. Ademais, em relação a atualização dos planos de manejo, os mesmos encontraram-se desatualizados desde a sua publicação nos anos 90, como verificado nas Unidades do estado da Bahia. Sendo assim, sugere-se que ao realizar as atualizações, os planos venham a incluir especificações direcionadas a incidentes com químicos, em especial o petróleo, além das demais ações antrópicas as quais os ambientes costeiros estão predispostos.

Palavras-chave: Desastre Ambiental, Gerenciamento Costeiro, Impacto Ambiental, Plano de Manejo.

ABSTRACT: *The advent of management mechanisms for Conservation Units (UCs) and coastal areas, in an integrated way, is fundamental in the processes of forecasting impacts and disasters, and in the creation of mitigation measures. Coastal zones are subject to great environmental vulnerability in terms of climate change, anthropogenic pressures, and chemical accidents at different scales. Thus, the present work aims to analyze the management plans of the Marine UCs affected by oil spills in the coastal zone of Brazil in 2019, in order to verify and analyze the presence of contingency plans, as well as the identification of possible proposed actions to mitigate that impact. With this research, it was verified that of the 119 Marine UCs in the affected states, only 42 management plans. Of these, 20 were in the influence area of spills, covering 26 municipalities in 7 states, however, none of them presented actions related to the contingency or mitigation of impacts related to chemical accidents in their management plan. Furthermore, in relation to the updating of the management plans, they were found to be outdated since their publication in the 1990s, as verified in the Units of the state of Bahia. Therefore, it is suggested that when performing the updates, the plans should include specifications aimed at incidents with chemicals, especially oil spills, in addition to other anthropic actions to which coastal environments are predisposed.*

Keywords: *Environmental Disaster, Coastal Management, Environmental Impact, Management Plans.*

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1. INTRODUÇÃO

As zonas costeiras são unidades espaciais que apresentam um desmedido valor socioeconômico, sendo fonte de serviços ecossistêmicos essenciais ao homem (Portman *et al.*, 2012), bem como no que tange a sustentabilidade ambiental (Taveira-Pinto *et al.*, 2020). No Brasil, a delimitação das zonas costeiras compreende uma área terrestre com seus limites demarcados pelos Planos Estaduais de Gerenciamento Costeiro, e no oceano por meio do Mar Territorial (12 milhas náuticas ou 22,2 km a partir da linha de base) (Oliveira e Nicolodi, 2012).

Devido a expressão territorial do Brasil, a sua zona costeira apresenta uma grande diversidade quanto a seus ecossistemas marinhos e costeiros (manguezais, marismas, dunas, baías, estuários, recifes de coral) (Diegues, 1999) em aproximadamente 8000 km de costa (Andrés *et al.*, 2018). Desse modo, é necessário um bom gerenciamento integrado para salvaguardar a qualidade ambiental dessas áreas.

Os questionamentos relacionados ao meio ambiente no Brasil, e posteriormente sua gestão, começaram a ganhar destaque a partir do ano de 1972, logo após a Conferência das Nações Unidas sobre Meio Ambiente Humano em Estocolmo (Suécia) e a publicação do Relatório de Brundtland, em 1987 (Martinez, 2007; Nascimento *et al.*, 2018). Esses marcos históricos fizeram com que os assuntos relacionados ao crescimento populacional e econômico, com a necessidade de desenvolvimento sustentável frente ao esgotamento de recursos naturais, tomassem força em ascender seus passos no país.

Com o surgimento das temáticas ambientais, ainda na década de 1980, começaram a desenvolver-se ideias voltadas à necessidade de ampliação de locais/regiões para proteção com um sistema único e integrador em âmbito nacional, na tentativa de conservar e proteger a natureza (Silva e Mello, 2019). Com isso, após quase duas décadas de formulação e burocracias, em 2000 foi sancionada a Lei 9.985, que instituiu o Sistema Nacional de Unidades de Conservação da Natureza (SNUC) no Brasil, a qual propõe diretrizes para as unidades de conservação (UCs) e as classifica em dois grandes grupos: o das unidades de conservação de proteção integral e o das unidades de conservação de uso sustentável, e suas categorias (BRASIL, 2000).

No que diz respeito ao litoral do país, mais exclusivamente no âmbito marinho, existem 187 UCs, sendo elas 79 (42,25%) de proteção integral distribuídas em Estações Ecológicas, Monumentos Naturais, Parques, Refúgios de Vida Silvestre e Reservas Biológicas e 108 (57,75%) de uso sustentável com Áreas de Proteção Ambiental, Áreas de Relevante Interesse Ecológico, Reservas de Desenvolvimento Sustentável e Reservas Extrativistas (MMA, 2020). Mesmo com a diversidade de UCs presentes no litoral brasileiro, o número ainda não é suficiente para proteger integralmente a costa, principalmente devido à expressão territorial juntamente com seu domínio oceânico, representando apenas 26,46% de Área Marinha Protegida, correspondente a uma área de 963.698,62 km² (MMA, 2020).

Em relação às UCs, a presença de um documento técnico norteador para a sua gestão, o plano de manejo, é essencial para fundamentar seus objetivos, bem como estabelecer normativas e zoneamento para utilização de áreas e o manejo dos recursos naturais (ICMBio, 2020). A Gestão Integrada de UCs e da Zona Costeira como um todo, surge como ferramenta fundamental e eficaz na previsão de estratégias para mitigação de impactos pré-existentes e suas futuras projeções (Moraes *et al.*, 2014; Phillips e Jones, 2006). Devido à sua exposição na costa e especulações econômicas para seu uso, as UCs Marinhas estão muito suscetíveis a impactos antrópicos, em que se destacam o turismo, as erosões, aquicultura, mineração marinha, deposição excessiva de sedimentos, derramamento de substâncias tóxicas, poluição, mudanças climáticas, dentre outros (Halpern *et al.*, 2007; Phillips e Jones, 2006; Potters 2013; Primavera, 2006; Van Dover, 2011).

Nesse contexto, no ano de 2019 foi detectado um imensurável impacto ambiental correspondente a um vazamento de óleo bruto no litoral do Brasil, sendo um dos maiores desastres ambientais por derrame de óleo do país e um dos mais extensos do mundo (Araújo *et al.*, 2020; Pena *et al.*, 2020), com volume vazado estimado em 5.000-12.500 m³ (Zacharias *et al.*, 2021). O óleo bruto, petróleo, apresenta em sua composição diversas partículas diferentes, com alto teor de toxicidade à saúde humana, além de ser prejudicial a toda a fauna e flora que tenha sido exposta a essas substâncias (Araújo *et al.*, 2020). O desastre pode ser considerado singular, visto que, além dos aspectos químicos e tóxicos do derramamento de óleo, consideraram-se as características da região e dos ecossistemas atingidos, a quantidade de áreas naturais protegidas que foram afetadas, e a ausência de medidas e ações na resolução e mitigação dessa problemática socioambiental (Soares *et al.*, 2020).

Os primeiros estados atingidos na costa brasileira foram na região nordeste, especificamente Pernambuco e Paraíba. Cerca de 4 semanas após a detecção do aparecimento da primeira mancha de óleo no litoral, ocorreram registros na região sudeste do país, no litoral norte do estado do Rio de Janeiro (Carmo e Teixeira, 2020) e Espírito Santo. Em pouco tempo, 11 estados costeiros foram atingidos pelas manchas de óleo em diferentes proporções (Alagoas - AL, Bahia - BA, Ceará - CE, Espírito Santo - ES, Maranhão - MA, Paraíba - PB, Pernambuco - PE, Piauí - PI, Rio de Janeiro - RJ, Rio Grande do Norte - RN e Sergipe – SE), causando danos irreversíveis à vida marinha. Portanto, devido ao grande poder de dispersão do produto, o monitoramento e identificação de regiões atingidas pelo derramamento de óleo é fundamental para que se tomem ações rápidas e eficazes de tratamento e dimensionamento do impacto (Yang *et al*., 2020).

O presente trabalho tem como objetivo analisar os planos de manejo das UCs Marinhas atingidas pelo derramamento de óleo na zona costeira do Brasil no ano de 2019, tendo em vista a verificação e avaliação da presença de planos de contingenciamento, bem como a identificação de possíveis ações propostas para mitigação do referido impacto nesses documentos.

2. METODOLOGIA

2.1 Levantamento das Unidades de Conservação Marinhas atingidas pelo derramamento de óleo

A identificação das UCs Marinhas presentes nos estados litorâneos brasileiros, atingidas pelo derramamento de óleo, foi dada por meio do Cadastro Nacional de Unidades de Conservação (CNUC). O CNUC é um banco de dados integrado, administrado pelo Ministério do Meio Ambiente (MMA) brasileiro, o qual apresenta informações padronizadas das UCs geridas pelas três esferas do governo (municipal, estadual e federal) e particulares.

Ao acessar ao CNUC, foram utilizadas as seguintes delimitações: Bioma Marinho; Presença de Plano de Manejo; Unidades de Federação (BA, CE, ES, MA, PE, RJ, RN). Posteriormente, foi verificada a localização de cada UC por meio do Instituto Socioambiental (ISA, 2020), indicando as coordenadas iniciais e finais de cada uma, possibilitando a sobreposição de dados entre essas coordenadas com as informações das planilhas de georreferenciamento do derramamento de óleo na costa, disponibilizadas online pelo Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis (IBAMA, 2020). Dessa maneira, tornou-se possível identificar também as praias atingidas de cada UC Marinha.

A busca e a conferência dos planos de manejo das respectivas unidades foram efetuadas por meio da verificação do banco de dados das agências e órgãos ambientais estaduais de meio ambiente, Instituto Chico Mendes de Conservação da Biodiversidade (ICMBio) e Instituto Socioambiental (ISA), fornecidos em meio digital.

2.2 Análise de dados

Feito o levantamento das UCs Marinhas existentes em cada Estado, foram investigadas as unidades atingidas pelo derramamento por meio do comparativo geográfico fornecido pelo IBAMA e veículos midiáticos (G1; O Globo) baseados em fontes da Marinha do Brasil e registros visuais do óleo no corpo d'água e areia.

A partir disso, foram analisados os planos de manejo para verificar a existência de um plano de contingenciamento para cada UC Marinha, com o auxílio das seguintes palavras-chave: derramamento de óleo, acidente químico; contingenciamento; catástrofes; desastres; enfrentamento; impacto ambiental; mitigação; óleo; plano de ação. Desta forma foi possível verificar nos planos a presença de ações preestabelecidas para enfrentar catástrofes e desastres naturais ou antrópicos. Esse procedimento permitiu aferir a eficácia desses planos de contingenciamento, analisando quais medidas foram tomadas, como estas impactam na prática da ação pretendida, no momento de execução, entre outros aspectos.

Foi realizado ainda um comparativo entre as unidades que possuem planos e/ou ações de contingenciamento em seus planos de manejo e aquelas que não possuem. Esse procedimento teve o objetivo de ressaltar a importância desses planos frente a um desastre, além de evidenciar as divergências entre eles, verificando as ações que impactam de maneira substancial a conservação da biodiversidade.

3. RESULTADOS E DISCUSSÃO

3.1 UCs Marinhas atingidas pelo derramamento de óleo

Com a pesquisa realizada no CNUC, foram encontradas 119 UCs Marinhas ao longo dessas unidades federativas litorâneas atingidas pelo derramamento de óleo: BA, CE, ES, MA, PE, RJ, RN. Ressalta-se que os estados de Alagoas, Paraíba, Piauí e Sergipe foram atingidos pelo derramamento de óleo, mas não se obteve registros de informações de suas UCs Marinhas na base de dados do CNUC até junho de 2020.

Das 119 UCs apenas 42 UCs apresentaram plano de manejo, representando 35% do total. Com o auxílio do comparativo geográfico disponibilizado pelo IBAMA, pôde-se constatar que 17 UCs Marinhas foram atingidas pelo derrame de óleo. Porém, salienta-se que os veículos locais de comunicação midiática informaram o acréscimo de 3 UCs (Parque Nacional Jericoacoara, Parque Nacional Lençóis Maranhenses e Reserva Extrativista Cururupu) totalizando 20 UCs Marinhas (Figura 1).

Dentre todas as unidades identificadas, 65% são Áreas de Proteção Ambiental (APAs). Essas áreas apresentam valores cênicos e/ou culturais com grande importância para a proteção dos ecossistemas e qualidade de vida da população local inserida. Em virtude disso, muitas dessas regiões apresentam um investimento turístico elevado, a exemplo da APA Caraíva Trancoso (BA), APA Guadalupe (PE), APA Jenipabu (RN) e APA Jericoacoara (CE). Dentre as outras unidades, 15% são Parques Nacionais, 10% são Parques Naturais Municipais, 5% são Reservas Extrativistas (Resex) e 5% Reserva Biológica (Rebio).

Ao todo, pôde-se verificar a presença de manchas de óleo em 26 municípios que incluem essas UCs Marinhas. A primeira ocorrência se deu em 3 de setembro de 2019, pelo IBAMA, na APA Santa Cruz (PE), mais precisamente na Praia do Forte Orange, Ilha de Itamaracá (Material complementar).

De todas as UCs Marinhas com plano de manejo atingidas pelo derramamento de óleo, o estado da Bahia foi o mais representativo, com 69,6% seguido de Pernambuco (14,5%), Rio Grande do Norte (5,8%), Ceará (4,3%), Maranhão (4,3%) e Espírito Santo (1,4%). Embora o estado do Rio de Janeiro tenha sido atingido, ressalta-se que nenhuma unidade desse Estado foi afetada pela mancha de óleo. Dada a sua capacidade de dispersão e influência das correntes marítimas, o óleo em pouco espaço de tempo se alastrou para outras UCs Marinhas sem apresentar nenhum padrão de distribuição aparente, o que dificultou o planejamento e execução de medidas preventivas pontuais nas praias, por não se saber ao certo quando e onde as manchas iriam aparecer.

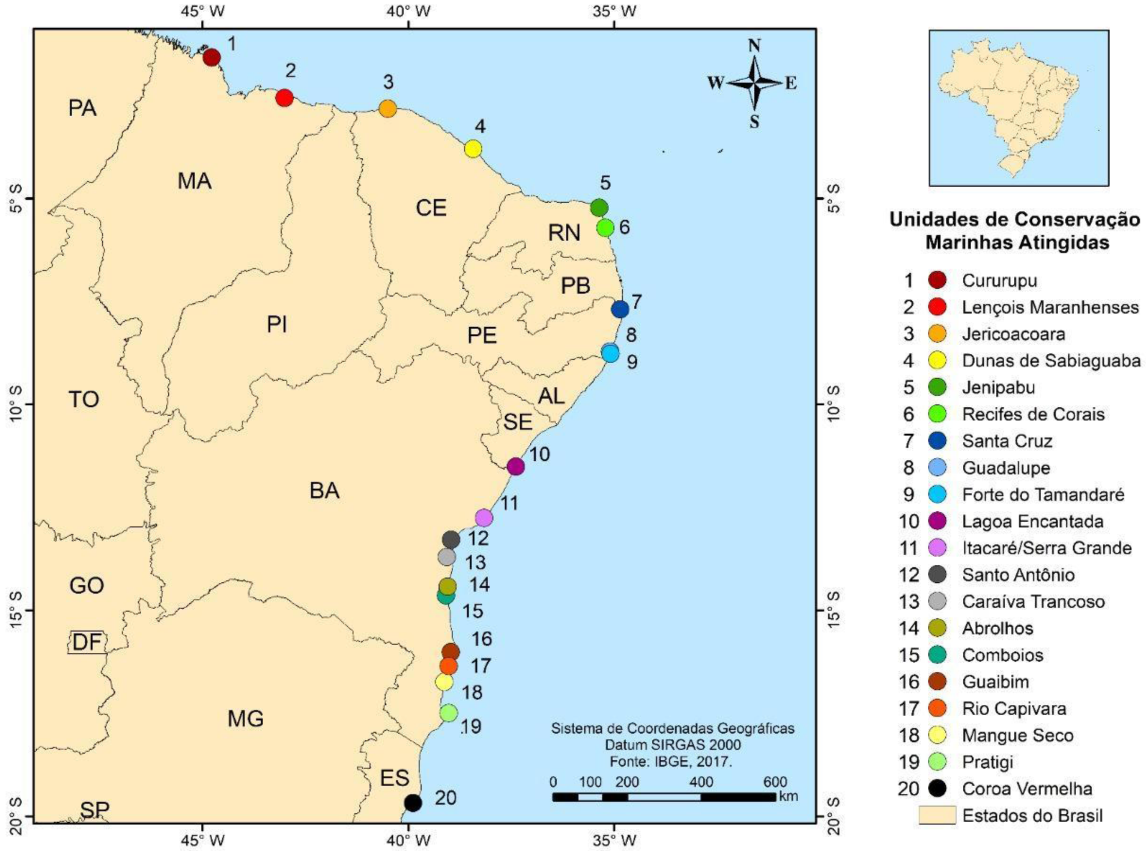

Figura 1. Unidades de Conservação Marinhas com planos de manejo, atingidas pelo derramamento de óleo na costa brasileira em 2019.

Observando de maneira geral o panorama das UCs marinhas do Brasil, pode-se verificar que, mesmo com toda a sua dimensão territorial, além de ser considerado um dos países com maior biodiversidade (Brandon *et al*., 2005), a região marítima do Brasil ainda é pouco protegida, de acordo com as recomendações mundiais (IUCN, 2003). Segundo Soares *et al*. (2011), há um incentivo por parte do Brasil na formulação de políticas públicas para proteger essa biodiversidade, aumentando as áreas protegidas em todos os ecossistemas que fazem parte do território brasileiro, compromisso assumido pelo Brasil como signatário da Convenção de Diversidade Biológica. Dessa maneira, o quantitativo de UCs Marinhas tende a aumentar com o evoluir do tempo.

Ainda que lento, pode-se observar uma crescente de UCs Marinhas no país. Segundo o estudo de Prates e Blanc (2007), até ao ano de sua realização, havia 121 UCs Marinhas, enquanto dados de 2020 indicam a evolução para 187 (MMA, 2020). Porém, mesmo com o avanço notório, os dados do presente artigo mostram que muitas das Unidades não apresentam planos de manejo, corroborando com as observações ressaltadas por Soares *et al*. (2011). Os autores enfatizam que a ausência de um plano de manejo, bem como falhas e até mesmo a inexistência de fiscalização adequada favorecem a vulnerabilidade de ações e impactos ambientais.

3.2 Análise dos Planos de Manejo das UCs Marinhas

A análise dos 20 planos de manejo das UCs Marinhas em estudo publicados até 2020, mostrou que nenhum apresentava um Plano de Contingenciamento (Tabela 1). Além disso, apenas as APAs Caraíva Trancoso, Costa de Itacaré, Lagoa Encantada e Santo Antônio, todas no estado da Bahia, apresentaram um plano de ação (Tabela 1). Porém, mesmo apresentando o plano de ação, nenhuma das unidades mencionadas fez alusão à atuação relacionada com desastres ambientais com óleo. Ademais, ressalta-se que o plano de manejo do Parque Nacional de Abrolhos fez menção a acidentes com derramamentos de substâncias químicas, porém, não menciona com especificidade os hidrocarbonetos, como é o caso do petróleo.

Tabela 1. Planos de manejo, ação e contingenciamento existentes nas Unidades de Conservação Marinhas atingidas pelo derramamento de óleo na costa brasileira em 2019.

Unidade de Conservação	**UF**	**Plano de Manejo**	**Plano de ação**	**Plano de Contingenciamento**
APA Caraíva Trancoso	BA	1998	sim	não
APA Coroa Vermelha	BA	1996	não	não
APA Costa de Itacaré	BA	2004	sim	não
APA Guaibim	BA	1993	não	não
APA Lagoa Encantada	BA	1996	sim	não
APA Mangue Seco	BA	1993	não	não
APA Pratigi	BA	2004	não	não
APA Rio Capivara	BA	2000	não	não
APA Santo Antônio	BA	1996	sim	não
Parque Nacional Abrolhos	BA	1991	não	não
Parque Nacional de Jericoacoara	CE	2011	não	não
Parque Natural Mun. da Dunas de Sabiaguaba	CE	2010	não	não
Reserva Biológica Comboios	ES	2018	não	não
Parque Nacional Lençóis Maranhenses	MA	2002	não	não
Resex Cururupu	MA	2016	não	não
APA Guadalupe	PE	2011	não	não
APA Santa Cruz	PE	2010	não	não
Parque Natural Forte do Tamandaré	PE	2012	não	não
APA dos Recifes de Corais	RN	Resumo Executivo[1]	não	não
APA Jenipabu	RN	2009	não	não

1 Síntese da proposta do plano de manejo com as principais informações do documento.

Pôde-se observar também que a maioria dos planos de manejo estão desatualizados, muitos não tiveram revisão desde a sua elaboração, como é o caso do Parque Nacional de Abrolhos e APA Guaibim (Tabela 1), sendo os mais antigos analisados. Essa falta de atualização no plano de manejo implica uma escassez de dados sobre as questões ambientais, sociais e históricas da unidade, o que impede o aperfeiçoamento dos planos a partir de problemas não previstos inicialmente.

A falta de dados e a não atualização de conteúdo dificultam a gestão das UCs, sejam marinhas ou não. De acordo com Kinouchi (2014), os planos de manejo são fortes instrumentos de apoio ao gerenciamento dessas unidades, ademais são fundamentais para articulação e orientação de gestores na formulação de tomadas de decisão frente aos problemas ambientais que venham a surgir. Além disso, Artaza-Barrios e Schiavetti (2007) dizem que essa ferramenta vem a contribuir com propostas que visam a manutenção e conservação da biodiversidade presente nas áreas naturais. Com essas informações, verifica-se que a falta de planejamento para inclusão de problemas passíveis de surgimento dificulta a tomada de decisão correta, favorecendo a perda de biodiversidade relacionada a impactos diretos e indiretos, como pôde ser verificado com o derramamento de óleo.

Infelizmente, acidentes com derramamento de óleo são comuns, sendo eles de acordo com Harr *et al.* (2018) uma das fontes de poluição marítima mais conhecidas. Além disso, vale ressaltar que devido ao seu poder de dispersão por correntes marinhas (Bispo *et al.*, 2012), o óleo favorece uma contaminação crônica e eventual da biota singularizando o efeito semeadura, segundo Soto *et al.* (2014).

Mesmo sendo uma das fontes de poluição marinha mais comuns e de grande potencial de toxicidade, com grandes registros na história a exemplo de Campeche - Golfo do México (1979), Atlantic Empress - Tobago (1979) e Nowruz - Golfo Pérsico (1983), chama-se a atenção para a ausência da inclusão desse potencial poluidor e seu grande poder de impacto nos planos de manejo das UCs Marinhas estudadas. Soto *et al.* (2014), ao estudarem o incidente de 1979 em Campeche, ressaltaram que a falta de informação relacionada ao óleo favoreceu a dispersão do material, bem como a difusão de impactos ambientais no ecossistema marinho.

Outro ponto é a falta de padronização identificada nos planos de manejo das UCs, uma vez que os planos não seguem as mesmas diretrizes de elaboração e desenvolvimento do conteúdo. A inclusão e o detalhamento das informações ficam a critério do corpo de especialistas a cargo da sua elaboração. Essa falta de padronização dificulta inclusive as ações de proteção à biodiversidade executadas pela gestão dentre as UCs. Além disso, verifica-se que muitos gestores sentem dificuldades em implementar os planos de manejo. Essa dificuldade não é apenas encontrada no Brasil, mas em outros países, como descrito por Lane (2003), além de ser um problema existente no planejamento que envolve recursos naturais (Lachapelle *et al.*, 2003).

As problemáticas e falta de informações presentes em planos de manejo, assim como retratado na presente pesquisa, vem corroborar com o estudo realizado por Dourojeanni (2003). O autor verificou que um dos grandes problemas existentes em planos de manejo das UCs no Brasil são as informações que constam neles, pois não tratam com exatidão as necessidades e peculiaridades existentes em cada região, trazendo informações ditas como utópicas, bem como a ausência de uma visão sistêmica integrando fatores socioambientais e econômicos aos planos.

4. CONCLUSÕES

O derramamento de óleo na zona costeira do Brasil atingiu 11 estados da federação. Das 119 UCs Marinhas presentes nos referidos estados, apenas 42 unidades (35%), apresentaram um plano de manejo. Dessas, 20 UCs Marinhas (48%) foram atingidas, abrangendo 26 municípios em 7 desses 11 estados. Nenhum dos planos de manejo analisados, incluindo o do Parque Nacional de Abrolhos que mencionou acidentes químicos em seu conteúdo, apresentou planos e/ou ações de mitigação de impactos voltados para o derrame de óleo ou acidentes químicos.

As unidades de conservação no Brasil não recebem por parte dos órgãos governamentais que as administram, a atenção merecida pelo papel essencial desempenhado na conservação da biodiversidade e serviços ecossistêmicos por elas prestados, e muitas ainda não apresentam plano de manejo. Segundo o SNUC, os planos de manejo devem ser elaborados até cinco anos depois da criação da unidade e revistos a cada 2 anos. De todas as unidades, apenas a Reserva Biológica de Comboios (ES) encontra-se atualizada em relação ao seu plano de manejo. Por outro lado, foram encontradas em algumas áreas, principalmente no estado da Bahia, planos elaborados na década de 90, sem nenhuma atualização desde então. Além da ressalva de necessidade de atualização, os planos de manejo não apresentam uma padronização de informações, ficando a sua elaboração a cargo da equipe técnica.

Dentre os planos de manejo que mencionaram um plano de ação, essas sessões focaram-se em impactos recorrentes na região em que se encontrava a UC Marinha, sem abordar possíveis impactos aos quais a região estaria vulnerável, como o derramamento de óleo e outros químicos. A menção desses impactos facilitaria o desenvolvimento de ações de políticas públicas e tomadas de decisão a gestores, e consequentemente planos de contingência para a mitigação dos impactos, caso o desastre acontecesse na região.

Com o incidente ocorrido, mesmo sem as UCs Marinhas apresentarem ações pré-estabelecidas a desastres com materiais químicos, as respostas das gestões em conjunto com os Estados e municípios foram fundamentais para a mitigação dos impactos. Todas as localidades atingidas estabeleceram planos emergenciais para monitoramento e ações de contenção para que o óleo não atingisse a maior parte da costa.

Com todas as análises realizadas neste estudo, sugere-se que durante a revisão dos planos de manejo dessas unidades sejam incluídos planos de ação voltados a desastres de origem antrópica, como o derramamento de óleo vivenciado em 2019 e/ou acidentes similares ocorridos no mundo, além dos demais impactos mais frequentes, aos quais as unidades estão predispostas devido a sua vulnerabilidade costeira. Dessa forma, as ações seriam realizadas de maneira pontual e concisa, aumentando a probabilidade de interrupção do prolongamento dos impactos ambientais.

CONTRIBUIÇÕES

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ENVIRONMENTAL IMPACTS ON MARINE ENERGY: COLLISION RISKS FOR MARINE ANIMALS AND PRIORITY SPECIES FOR MONITORING IN BRAZIL

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ABSTRACT: Brazil has great potential for the development of technologies for the conversion of marine energy from waves and tides, which raises the discussion about the possible environmental impacts of these projects. This article seeks to synthesize knowledge about the risks of collision of marine animals, such as mammals, fish and birds, with marine renewable energy (MRE) devices, as well as to identify priority species for environmental monitoring along the Brazilian coast. The risk of marine mammals colliding with MRE devices is influenced by regional and behavioral factors. The risk of collision in a fish community is influenced by the avoidance behavior, the distribution of fish in the MRE sites and the stages of the enterprise (installation, operation and maintenance). Seabird collision risk is influenced by species behavior (geographical distribution, seasonal habitat use, diving time and depth) and the location of MRE structures (surface and/or water column). The survey of priority species for monitoring the risk of collision with MRE devices in Brazil consisted of 5 species of marine mammals, 13 taxa of seabirds, 5 species of endangered sea turtles and 18 species or groups of species of fish of economic importance to the country. The research review did not record the occurrence of collisions with marine animals. However, this does not mean that they did not occur, but that they may not have been observed due to monitoring challenges. The study concluded that research on the interaction of marine animals with MRE devices should be encouraged, even in prototypes and non-commercial projects, in order to reduce knowledge gaps and support the development of MRE in an environmentally sound manner.

Keywords: Marine renewable energy, Collision risk, Species, Marine animals.

RESUMO: *O Brasil possui grande potencial para o desenvolvimento de tecnologias de conversão de energia marinha das ondas e marés, o que aflora a discussão sobre os possíveis impactos ambientais desses empreendimentos. Este artigo busca sintetizar os conhecimentos sobre os riscos de colisão de animais marinhos, como mamíferos, peixes e pássaros, com dispositivos de energia marinha renovável (EMR), bem como identificar as espécies prioritárias para o monitoramento ambiental ao longo da costa brasileira. O risco de colisão de mamíferos marinhos com dispositivos de EMR é influenciado por fatores regionais e comportamentais. O risco de colisão em comunidade de peixes é influenciado pelo comportamento de evasão, a distribuição dos peixes nos locais de EMR e as etapas do empreendimento (instalação, operação e manutenção). O risco de colisão de aves marinhas é influenciado pelo comportamento das espécies (distribuição geográfica, uso sazonal do habitat, tempo e profundidade de mergulho) e pela localização das estruturas de EMR (superfície e/ou coluna de água). O levantamento de espécies prioritárias para o monitoramento do risco de colisão com dispositivos de EMR no Brasil foi constituído por 5 espécies de mamíferos marinhos, 13 táxons de aves marinhas, 5 espécies de tartarugas marinhas ameaçados de extinção e por 18 espécies ou grupos de espécies de peixes de importância econômica para o país. A revisão das pesquisas não registrou ocorrência de colisões com animais marinhos. No entanto, não significa que não ocorreram, mas que podem não ter sido observadas devido aos desafios do monitoramento. O estudo concluiu que as pesquisas de interação de animais marinhos com dispositivos de EMR devem ser fomentadas, mesmo que em protótipos e projetos não comerciais, a fim de reduzir as lacunas do conhecimento e auxiliar o desenvolvimento da EMR de forma ambientalmente adequada.*

Palavras-chave: *Energia renovável marinha, Risco de colisão, Espécies, Animais marinhos.*

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1. INTRODUCTION

The Intergovernmental Panel on Climate Change (IPCC) preliminary report reveals that the world temperature rise will reach or exceed 1.5°C between 2021 and 2040 (IPCC, 2021). Its content is a warning to the end of the fossil fuel era, and the need for massive investments in renewable energy is irrefutable. For the scenario of temperature increase below 1.5°C, the share of renewable energy in the world is expected to grow from 14% in 2018 to 74% in 2050, which requires an eight-fold increase in the annual growth rate (IRENA, 2021).

Since 2019, the IPCC has recognized Marine Renewable Energies (MRE) as a mean of mitigating climate change. The ocean can be considered an enormous reservoir of thermal energy, heat from the sun, and mechanic energy from tides and waves. Technologies can generate electrical energy from various ocean energy resources such as tides, waves, ocean thermal energy conversion (OTEC), ocean currents, wind and salinity gradients (Spellman, 2014). Ocean energy resources can potentially generate between 45 000 TWh and 130 000 TWh of electricity per year, covering more than twice the global demand for electricity (IRENA, 2020). However, the contribution of marine energy to world electricity generation and needs is nowadays very small, representing 0.1%, coming mostly from tidal power plants (EPE, 2020a).

The Brazilian energy matrix is composed of approximately 50% of renewable energies (EPE, 2021) and these sources dominate the electricity sector, accounting for more than 80% of the country's electricity generation, Figure 1.

According to the 2020 National Energy Balance, Brazil does not use RME for electricity generation, despite the extensive coastal zone of 8 698 km (MMA, 2008; EPE, 2020b) and research indicating a potential of 114 GW of the renewable energies from the sea. A survey carried out by the Federal University of Rio de Janeiro (UFRJ), through local measurements and theoretical research, estimated an energy potential of 27 GW from the tides in the north and northeast regions of Brazil. On the coast of the states of Amapá, Pará and Maranhão, tides vary between 5 to 11 m (Florêncio and Trigoso, 2020; Tolmasquim, 2016). The energy potential of the waves was estimated from the extent of each state of the federation, based on the average significant wave height in the year and the average period in the year (Tolmasquim, 2016). Thus, the energy potential of the waves was 22 GW in the Northeast, 30 GW in the Southeast and 35 GW in the South (Tolmasquim, 2016; Florêncio and Trigoso, 2020, Figure 2).

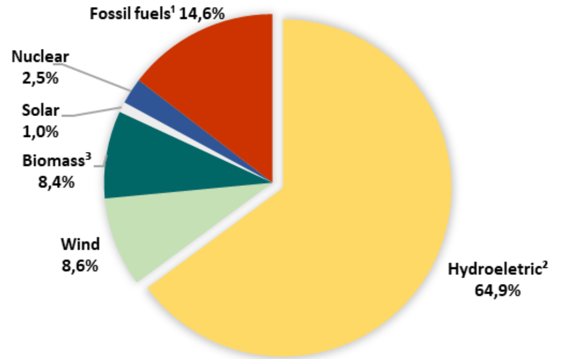

Figure 1. Domestic electricity supply of 651.3 TWh in Brazil, in 2019, by source. (Source: Adapted from the Energy Research Company (EPE, 2020b)). Notes: ¹Includes coke oven gas. ²Includes electricity imports. ³Includes firewood, sugarcane bagasse, bleach and other recoveries.

Despite the benefits of renewable sources, several studies reveal environmental impacts on renewable energy projects, which vary in type and intensity according to the technology used, geographic location, ecological resources, among other factors (Spellman, 2014). According to data from the International Energy Agency - IEA (2020), the share of renewable energies in electricity generation increased from 20% to almost 28% between 2010 and 2020. In view of the increasing trend in renewable sources, it is necessary to gather information about the impacts generated to mitigate or eliminate them.

Knowing them helps regulatory agencies in the authorization and licensing processes; and also helps government spheres responsible for the management of coastal and oceanic areas and project developers to understand what will be required from them, investing in technologies that improve maritime energy devices (Copping *et al*., 2020). Furthermore, it is vitally important to make the population of the coastal zone more aware of the environmental impacts of developments in this area (Barros *et al*., 2010). For example, when the population understands the advantages and disadvantages for the region, they may or may not oppose the implementation or permanence of renewable marine energy projects.

The exploration of ocean energy has few ventures and projects; however, like all energy exploration for human use, it also generates environmental costs (Copping *et al*., 2014). Installation and operation of RME have environmental impacts on marine animals (Keenan *et al*., 2011; Halvorsen *et al*., 2012) and physical systems (Ahmadian *et al*., 2012; Jones *et al*., 2014). This review presents research works that assess the interaction

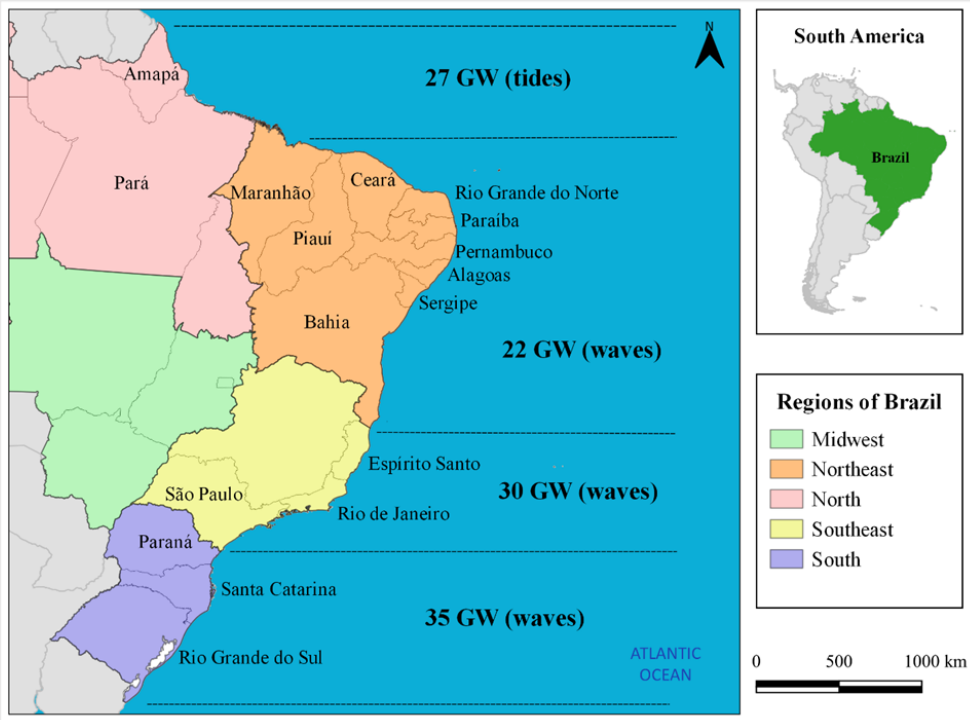

Figure 2. Estimated Brazilian theoretical potential of wave and tidal energy.

and collision risks of marine animals (mammals, fish and birds) with marine energy system of waves, tidal and currents; and since there is an estimated energy potential for the entire coast, it aims to indicate priority species for environmental monitoring of the risk of collision in Brazil.

2. METHODOLOGY

The survey on the potential environmental impacts of Marine Renewable Energy took place through the works of Spellman (2014), Tolmasquim (2016) and Copping *et al*. (2020). The summary of the state of the art on marine animal collision risk was based on Copping *et al*. (2020), report prepared by the Technological Collaboration Program in Ocean Energy Systems (OES) - Environmental. This intergovernmental program was developed to examine the environmental effects of marine energy and was established by the International Energy Agency in 2001.

The report features various laboratory, field and modeling researches, as well as international environmental monitoring programs, both to assess the interaction of marine animals and the risk of collision with RME devices. The great concern of these researches are endangered species and those of commercial and recreational importance, as additional disturbances in these populations can cause environmental and economic impacts. Therefore, to prepare a list of priority species for monitoring interaction with RME devices in Brazil, commercially important fish species were selected; and endangered species of marine mammals, birds and reptiles. The species of mammals, birds and reptiles were selected from ICMBio (2018) which used the IUCN (2001) method to categorize the risk of extinction.

According to MMA Ordinance No. 43/2014, of the Brazilian Ministry of the Environment, species threatened with extinction are those categorized as: vulnerable (VU), high risk of extinction in nature; Endangered (EN), very high risk of extinction; critically endangered (CR), extremely high risk of extinction; and extinct in the wild (EW), individuals only in cultivation, captivity or with a population (or populations) naturalized outside their natural range (ICMBio, 2018). Also for mammals, birds and reptiles, the category of extinction risk, the geographic distribution in the country, the habitat, and only for marine mammals, the presence in conservation units were informed. The fish species selected were those that make up 60% of marine fisheries production in Brazil, according to data collected by Dias-Neto and Dias (2015). From this work, the information selected was about the fishing area, habitat, average production between 1995 and 2010 in tons and the status of use or source (condition of fish stocks according to exploitation, which demonstrates the tendency to decline or population recovery) by species or group of fish species.

In the report by Copping *et al*. (2020), no research has been carried out about the risk of collision of marine animals with EMR devices in Brazil. Thus, it was not possible to identify the interaction of species of mammals, birds and fish in Brazilian territory with EMR devices. However, the species monitored in the research by Copping *et al*. (2020) were verified in publications in order to verify the occurrence in Brazil. Mammal species were consulted in ICMBio (2018) and Monteiro-Filho *et al*. (2013). Bird species were verified in ICMBio (2018) and Piacentini *et al*. (2015). And fish species were researched in ICMBio (2018) and Froese and Pauly (2021). In the research gathered by Copping *et al*. (2020) monitoring of reptile species was not observed.

3. ENVIRONMENTAL IMPACTS ON THE DEVELOPMENT OF MARINE RENEWABLE ENERGIES DEVICES

Several projects in Brazil and abroad developed ocean energy conversion technologies; however, most projects implemented in water were for testing or limited demonstration, with few commercial scale projects (Florencio and Trigoso, 2020; IRENA, 2020). Most of the environmental impact studies of these technologies were carried out as a requirement of regulatory agencies for the consent of commercial projects. In general, extensive monitoring is required to understand possible interactions of EMR devices with marine animals and habitats. However, not all instrumentation and/or data collection efforts to carry out this type of monitoring have achieved their objectives (Copping *et al*., 2020). This occurs because EMR devices are usually deployed in high energy and/or turbid places, which makes the operation of oceanographic equipment, sensor platforms and even human observation on vessels necessary to characterize these interactions difficult.

In this context, the article reviews studies on the potential risk of collision in RME devices, by examining the interactions between marine energy systems harvesting and the marine environment, called stressors and receptors, respectively, as designated by Boehlert and Gill (2010). Stressors are any part of RME systems that can cause damage or stress to a marine animal, a habitat, ecosystem processes or oceanographic processes. These stressors include moving turbine blades, anchors or foundations, mooring ropes, energy export cables, and emissions from any part of the RME system. Receptors include marine animals that live in the vicinity of an RME project, habitats where devices are deployed, and oceanographic processes such as natural water movement, wave height, sediment transport, and concentrations of dissolved gases and nutrients that sustain marine life (Copping *et al*., 2020). The interactions between stressors and receptors are analyzed through observations, laboratory and field experiments, and modeling studies (Copping *et al*., 2014; 2020). Figure 3 demonstrates some stressor-receptor

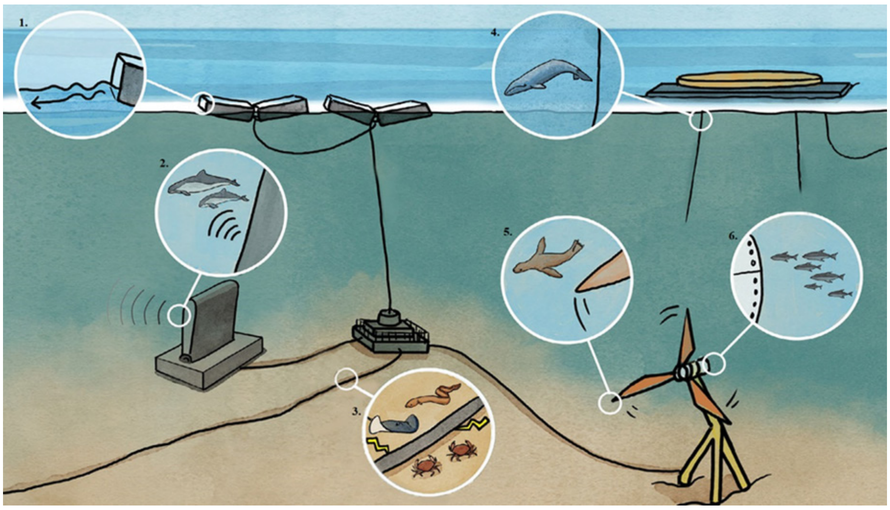

Figure 3. Potential interactions between stressor and receptor. 1. Changes in oceanographic systems; 2. Underwater noise; 3. Electromagnetic fields; 4. Mooring entanglement; 5. Collision risk and 6. Habitat changes after introduction of an RME device (Adapted from Copping *et al.*, 2020).

interactions.

It is noteworthy that the risks that RME devices can pose to marine animals, habitats and the environment vary according to the attributes of the RME device (static or dynamic), energy conversion technology (waves or tides) and scale installation space (single device or matrix) (Copping *et al*., 2020). In addition, to assess the actual environmental impacts of the EMR, local investigation actions must be carried out, generally foreseen for the consent of projects: carrying out baseline surveys before project implementation, aiming to understand, quantify and assess potential environmental impacts; analysis of cumulative effects of both human activities and natural processes; determination of the project's near and far field; and preparation of environmental monitoring to assess the impacts of the project's post-installation devices.

Research related to local investigation actions should seek efforts to gather inventory information of natural species in the region and their respective patterns of distribution and normal movement in time and space (cf. Viehman *et al*., 2018; Holdman *et al*., 2019); the characteristics of RME stressors (cf. Nedwell and Brooker, 2008); and the hydrodynamic and sedimentation pattern and its variation in time and space (cf. Fairley *et al*., 2017; Khaled *et al*., 2019).

Environmental impacts of the development of RME on marine animals

Marine energy harvesting systems can harm marine animals and their habitats. Scientific research carried out focuses on the following interactions of risk to marine animals: collision with mobile and stationary devices; underwater noise generated by devices; electromagnetic fields emitted by electrical cables and devices; and entrapment in underwater cable and mooring systems. The devices can also cause changes in benthic and pelagic habitats (Copping *et al*., 2020).

Risk of collision of marine animals with mobile and stationary devices

There is great concern about marine animals colliding with moving parts of a device, such as turbine blades, moving devices such as tidal kites and blade oscillators, or stationary parts of devices such as the foundation, which can cause irreversible injury or death. For species that are already being disturbed by other human activities, losing individuals can harm the survival of the entire population. Therefore, existing environmental monitoring programs in marine energy harvesting projects are aimed at declining marine mammal populations or those in protected areas; commercially important fish species and recreational fishing; and endangered seabirds (Copping *et al*., 2020). There are no reports in the literature of collisions of marine mammals, diving seabirds and other animals with RME devices, only interaction of fish with turbines without harmful effects (Matzner *et al*., 2017; Sparling *et al*., 2020).

Several collision risk models have been developed to predict the probability of collision and consequences in marine mammals (Wilson *et al*., 2007; Band, 2014). Collision potential will likely vary with local parameters such as location, water depth and tidal velocity, and with behavioral parameters of these animals such as vertical distribution in the water column, swimming in tidal currents and foraging sites. However, changes of behavior according to locations does not allow for generalization (Copping *et al*., 2020). Behavioral studies were carried out with harbor porpoises *Phocoena phocoena* (Macaulay *et al*., 2015, 2017; Benjamins *et al*., 2017), harbor seals, *Phoca vitulina* (Hastie *et al*., 2016) and gray seals *Halichoerus grypus* (Lieber *et al*., 2018). Studies such as Copping and Grear (2018) apply several input parameters and investigate the sensitivity in collision models.

Field and laboratory studies identified evasion behavior of marine mammals from locations where turbines were in operation. Overall, these animals kept an intermediary distance (hundreds of meters) from these devices, as indicated by environmental monitoring by the companies MayGen and Nova Innovation in Scotland, SeaGen in Northern Ireland, FORCE and Sustainable Marine Energy in Canada (Sparling *et al.*, 2020). Most mammal encounters occurred when the devices did not operate. More details on these studies can be found in Sparling *et al.* (2020). The preventive behavior (evasion) of these animals in the vicinity of tidal energy structures reduces the chances of collision. Collision risk modeling research should consider the avoidance rate for proper prediction. However, studies on the consequences of evasion of these animals for the region's ecosystem must be carried out.

In studies carried out to understand the interaction of fish with RME devices, unlike marine mammals, show evasion behavior on a fine scale (from centimeter till meter scale) while turbines are operating (Bevelhimer *et al.*, 2017); however, a third of the juvenile fish analyzed by Matzner *et al.* (2017) pass through turbines. To understand the avoidance behavior, laboratory research carried out in gutters showed that ray-finned tamoroks (*Gnathopogon elongatus*) are less able to avoid turbines in current locations (Yoshida *et al.*, 2020) and that the frequency of rotation of turbines significantly affected the avoidance behavior of Japanese rice fish (*Oryzias latipes*) (Zhang *et al.*, 2017). Avoidance behavior reduces the risk of collision, but these studies may indicate that local, device and fish factors, such as age, hinder this preventive action, and may increase the risk of collision in fish.

The distribution of fish in the region of marine energy harvesting systems is an important parameter for the risk of collision, as it indicates environmental factors that approach or distance fish from RME devices. Baseline surveys by Viehman and Zydlewski (2017) and Viehman *et al.* (2018) reveal that fish abundance and vertical distribution varied with season, daily cycle and tidal stages. These surveys used hydroacoustic data, which did not allow identifying the species at the survey sites. However, the authors used previous sampling to discuss the results. Viehman and Zydlewski (2017) indicated species likely to be present in the Bay of Fundy, Cobscook Bay, Maine, such as Atlantic herring (*Clupea harengus*), winter flounder (*Pseudopleuronectes americanus*), alewife (*Alosa pseudoharengus*), rainbow smelt (*Osmerus mordax*), blueback herring (*Alosa aestivalis*), American eel (*Anguilla rostrata*) and Atlantic mackerel (*Scomber scombrus*). Viehman *et al.* (2018) used samples from the Minas Passage Basin, Nova Scotia study site, and other parts of the Bay of Fundy in Canadá to determine species potentially present in the area, such as alewife (*Alosa pseudoharengus*), blueback herring (*Alosa aestivalis*), American shad (*Alosa sapidissima*), Atlantic salmon (*Salmo salar*), striped bass (*Morone saxatilis*), rainbow smelt (*Osmerus mordax*), sea lamprey (*Petromyzon marinus*), Atlantic sturgeon (*Acipenser oxyrhynchus*), American eel (*Anguilla rostrata*), Atlantic mackerel (*Scomber scombrus*), pollock (*Pollachius virens*), spotted stickleback (*Gasterosteus wheatlandi*), Atlantic herring (*Clupea harengus*), three-spine stickleback (*Gasterosteus aculeatus*) and sharks, in summer, as porbeagle (*Lamna nasus*) and spiny dogfish (*Squalus acanthias*).

Whitton *et al.* (2020) verified that vertical migrations were stimulated by the penetration of light into the water column and by particulate matter suspended in a sectional area. In this study, carried out with schools of sprat (*Sprattus sprattus*) and some of *Merlangius merlangus*, the fish remained in the device locations for only 6% of the operating time, revealing a very low collision risk. In addition to environmental factors, the stages of the marine energy project also influence the distribution of these animals. Staines *et al.* (2019) observed lower fish density during installation and maintenance periods than during normal operation of the RME device in Cobscook Bay, Maine, USA. This may indicate less potential for fish collisions in the installation and maintenance stages of marine energy systems, but greater migration. As the research used hydroacoustic data, it was not possible to identify the species that could be migrating from the area.

The availability of prey close to marine energy system structures is a parameter related to collision risk. The results obtained by Fraser *et al.* (2018) when comparing an area of RME devices with a nearby control site indicated an attraction of fish to RME devices (general increase in the observation of schools, mainly at night, and in wakeful flow). Although aggregation and vertical distribution depends on tidal phases and avoidance of device depth at high flow speed, increased fish in RME sites can lead to foraging behavior of larger predators such as marine mammals and birds, increasing the risk of collision of these species (Fraser *et al.*, 2018). The study was carried out in the Orkney Islands, Scotland, and according to the authors, the fish species likely to be present during data collection were mackerel (*Scomber scombrus*), pollack (*Pollachius pollachius*), saithe (*Pollachius virens*), sprat (*Sprattus sprattus*), herring (*Clupea harengus*) and sandeels (*Ammodytes spp.*).

Likewise, Williamson *et al.* (2019) pointed out the aggregation and concentration of fish close to turbine structures, which could attract the foraging of predators and, consequently, increase the risk of their collision. In addition, it was observed that predatory fish began to occupy deeper areas at night, which can result in greater energy expenditure and increase the risk of collision with operating turbines, due to poor visual detection in low light, with insufficient detection of changes in the flow field or noise for an avoidance action. The authors reported using observational data on fish behavior change in models that estimate the cumulative effects on the predator population and in ecosystem models. Due to the high tidal energy conditions, it was not possible to use trawls to distinguish the species. However, other studies have suggested possible species present at the site, such as Atlantic mackerel (*Scomber scombrus*), Atlantic herring (*Clupea harengus*), sprat (*Sprattus sprattus*), sandeel (*Ammodytes spp.*), haddock (*Melanogrammus aeglefinus*), ling (*Molva molva*), saithe (*Pollachius virens*), Atlantic cod (*Gadus morhua*), butterfish (*Pholis gunnellus*), scorpion fish (*Taurulus bubalis*) and pollack (*Pollachius pollachius*) (Williamson *et al.*, 2019).

Collision risk or encounter risk models (also used to estimate the probability of the animal occupying the same space as the device) typically use a physical description of the turbine and fish characteristics to estimate the potential collision rate. Studies even in worst-case scenarios have revealed small collision/encounter risk rates for fish, such as Shen *et al.* (2016) and Grippo *et al.* (2017), in Maine, in the United States; and Xodus Group (2016), in the Orkney Islands, Scotland.

Seabirds dive at operational turbine depths, presenting a collision risk that involves various behavioral movements, such as geographic distribution, seasonal habitat use, diving time and depth, among others (Sparling *et al.*, 2020). Thus, the behavior of seabirds can increase or reduce the risk of collision. In the following studies, behavior determined an increased risk of collision due to: diving depth in European shags (*Phalacrocorax aristotelis*) and black guillemot (*Cepphus grylle*) (Langton *et al.*, 2011; Furness *et al.*, 2012); the association with sites of rapid horizontal flow, such as Atlantic puffins (*Fratercula arctica*) (Waggitt *et al.*, 2016); and foraging terns (*Sterna sandvicensis, Sterna hirundo, Sterna paradisaea*) on device mats (ecological trap) (Lieber *et al.*, 2019). In addition to that, the location of RME structures, such as floating wave energy devices on the surface, can increase the risk of collision due to their use for resting seabirds, especially Arctic terns (*Sterna paradisaea*), Jackson *et al.* (2014). Collision risks were considered lower when the probability of diving close to turbines was greater in high tides than in ebb tides, and when this probability was lower in faster tidal flow (Cooper *et al.*, 2020), according to a study made with black guillemots (*Cepphus grylle*), European shags (*Phalacrocorax aristotelis*), Atlantic puffins (*Fratercula arctica*), Northern gannets (*Morus bassanus*), common guillemots (*Uria aalge*) and red-throated divers (*Gavia stellata*).

Despite these studies, foraging sites and diving behavior are highly variable among bird species, habitat use is site-specific and may vary within a site (Sparling *et al.*, 2020), making it difficult to calculate a specific risk even for the studied region. Therefore, the Scottish Natural Heritage (2016) guidance for collision risk models (using turbine and animal pattern data for estimation) can be used to choose a model suitable for the specific circumstance of the enterprise and the available data, thus avoiding generalizations.

4. PRIORITY SPECIES FOR MONITORING THE RISK OF COLLISION WITH MARINE RENEWABLE ENERGY HARVESTING SYSTEMS IN BRAZIL

Brazil was the first country in Latin America to install a wave plant, located in the port of Pecém, in the state of Ceará. In the Bacunga estuary, in the state of Maranhão, studies point to the technical feasibility of installing a tidal power plant (Ferreira and Estefen, 2009). Although the projects are not in force, the existence of dozens of bays with tidal heights between 3.7 and 8 m along the north coast of the country, and the announcement of the partnership between the Pecém Complex and the Swedish-Israeli company Eco Wave Power, for the implementation of a clean wave energy generation plant by the Ceará government, accelerate the concern with the Brazilian marine fauna (Piacentini, 2016; Ceará, 2021). In this section, a brief review of marine species found off the Brazilian coast susceptible to the risk of collision with marine renewable energy devices was carried out.

4.1 Marine mammals

In Brazil, 56 species of marine mammals have been found by 2020, of which 47 belong to the Cetacea order (whales, dolphins, porpoises), one species belongs to Sirenia and eight belong to Carnivores (seals, fur seals, elephant seal) (Santos, 2021a). Many of these marine species are called "vagant", as they are occasional visitors to the Brazilian coast and are not part of the national survey on the risk of extinction published in 2018. According to this survey, eight species were considered threatened, with the main threats being pollution, including noise, collision with vessels and accidental fishing (ICMBio, 2018). Table 1 groups the species of marine mammals that are threatened and found in conservation areas. These species deserve special attention in monitoring the risk of collision with RME devices and vessels, when the installation, operation and maintenance of the enterprise are carried out.

RME projects are developed to operate in the coastal zone up to the maritime limit of the Exclusive Economic Zone – EEZ. These zones are located within the continental shelf according to the boundaries shown in Figure 4. Thus, the threatened species of the order Cetacea, *Balaenoptera borealis* (sei whale), *Balaenoptera physalus* (fin whale) and *Balaenoptera musculus* (blue whale) were not included in the Table 1, as records on the continental shelf are rare.

This survey does not aim to exclude the monitoring of other species of marine mammals (whales, dolphins, seals, fur seals, etc.) occurring in Brazil in areas where marine energy systems are deployed, because species that are not threatened must maintain or improve its state of conservation.

The species *Phocoena phocoena* (harbor porpoises), *Phoca vitulina* (harbor seal) and *Halichoerus grypus* (grey seals)

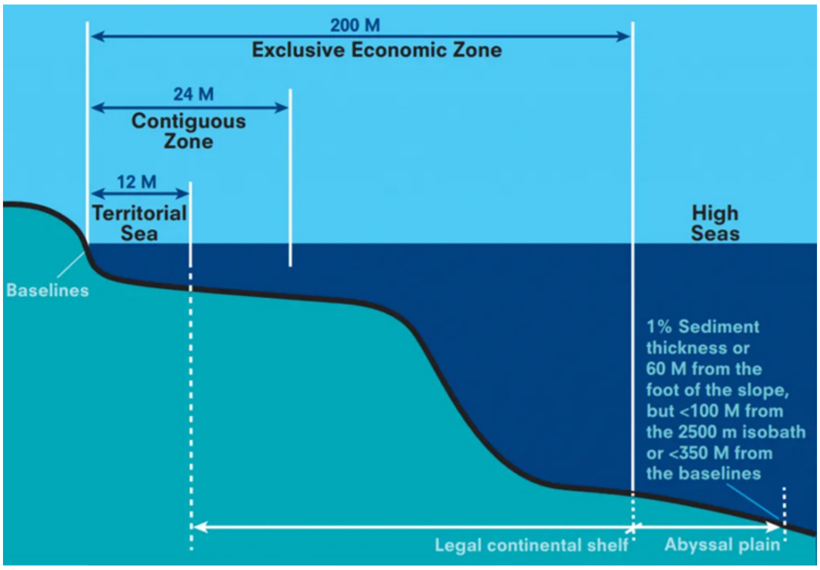

Figure 4. Maritime zones under the United Nations Convention of the Law of the Sea – UNCLOS (UNCLOS, 2012).

Table 1. Endangered species of marine mammals found in Brazilian protected areas (ICMBio, 2018; Monteiro-Filho *et al.*, 2013).

Order	Species	Common name	Category of extinction risk / Geographical distribution in Brazil / Presence in protected areas
Cetacea	*Physeter macrocephalus*	Sperm whale	Vulnerable species. Occurrence throughout the Brazilian coast, mainly in oceanic habitat. Rio Grande do Norte: REBIO Atol das Rocas. Santa Catarina: - APA Baleia Franca and REBIO Marinha do Arvoredo.
Cetacea	*Sotalia guianensis*	Guiana dolphin	Vulnerable species. Occurrence from the state of Amapá to Santa Catarina, mainly in coastal ecosystems such as bays, inlets and estuaries. The Guiana dolphin is found in 162 Brazilian conservation units, however, only the APA of Anhatomirim (SC) and REFAU Tibau do Sul (RN) have among their objectives the protection of the species.
Cetacea	*Eubalaena australis*	Southern right whale	Endangered species. Occurrence from the state of Bahia to Rio Grande do Sul, being recorded, in most cases, in places less than 10 m deep. Bahia: PARNA Marinho de Abrolhos, APA Ponta da Baleia; Santa Catarina: APA Baleia Franca; Rio Grande do Sul: REVIS Ilha dos Lobos, potentially, PARNA Lagoa do Peixe.
	Pontoporia blainvillei	Franciscana whale	Critically endangered species. It occurs from the state of Espírito Santo to Rio Grande do Sul; its preferred habitat includes coastal regions up to 50 m deep and some estuarine complexes. The species occurs in more than 70 conservation units.
Sirenia	*Trichechus manatus*	West Indian manatee	Endangered species. It occurs in the state of Alagoas, Pernambuco to the east of Ceará, appearing again on the west coast of Ceará to the Parnaíba delta, in Piauí. It reappears on Ilha do Gato, on the east coast of Maranhão, as far as the municipality of Oiapoque, in Amapá state. Alagoas: APA Piaçabuçu; Pernambuco/Alagoas: APA Costa dos Corais; Paraíba: ARIE Manguezais da Foz do Rio Mamanguape, RESEX Acaú-Goiana, APA Barra do Rio Mamanguape; Ceará: RESEX Prainha do Canto Verde; Maranhão/Piauí/Ceará: APA Delta do Parnaíba; Maranhão: RESEX Cururupu and Quilombo do Frexal; Pará: RESEX Chocoaré-Mato Grosso, São João da Ponta, Mãe Grande de Curuçá, Maracanã, Gurupi-Piriá, Marinha de Caeté-Taperaçu, Marinha de Tracuateua, Marinha de Soure; Amapá: ESEC Maracá-Jipioca, PARNA Cabo Orange.

Note: The following are Portuguese acronyms whose meanings have been translated into English: APA - Environmental Preservation Area; ARIE – Area of Relevant Ecological Interest; ESEC – Ecological Station; PARNA – National Park; REBIO - Biological Reserve; REFAU – Fauna Reserve; RESEX – Extractive Reserve and REVIS – Wildlife Refuge.

are not found on the Brazilian coast but were surveyed in Europe, and studies assessed their behavior with underwater devices and the risk of collision. This fact attests the need for conducting similar research on the installation and operation of these systems in Brazil. In addition, the behavioral differences of animals in nearby locations reaffirm the need for research on the interaction of Brazilian marine mammals (receptors) with RME devices and turbines (stressors).

4.2 Marine fish community

In Brazil, more than 1 300 species of marine fish are known, of which 98 have been classified as threatened with extinction. Of the species threatened with extinction, 72 were registered in conservation units, which keep the integrity of portions of the habitat, contributing to its preservation. It is advisable, in areas where RME systems are installed, to observe the occurrence of species threatened with extinction on the list of the Ministry of the Environment, according to Ordinance No. 445/2014.

According to Copping *et al*. (2020), commercially important fish species are included in the environmental monitoring carried out in international marine energy undertakings. The extinct Ministry of Fisheries and Aquaculture, in 2012, listed 121 species or groups of fish, 12 crustaceans and 10 molluscs (total: 143) as part of the marine biodiversity of commercial fisheries. From this biodiversity, 25 species or group of species are responsible for about 60% of the marine fishery production in Brazil. These species had an average production of more than 4 000 tons or relevant social and economic importance for national marine fisheries from 1995 to 2010 (Dias-Neto and Dias, 2015).

Table 2 presents the 18 main species or group of fish species of economic importance for Brazil. Crustacean species, such as shrimp, lobsters and crabs, were removed as they are not the target of this article. Table 2 also informs the use status of this set of species or group of fish species. Marine fish produced by aquaculture were not considered, as this activity usually takes place in a confined and controlled space. Thus, they would hardly be part of a collision risk analysis with RME devices.

In addition to the related species, the following are important for Brazilian commercial fisheries: swordfish (*Xhipias gladius)*, common dolphinfish (*Coryphaena hippurus*), king mackerel (*Scomberomorus cavalla*), blackfin tuna (*Thunnus atlanticus*), frigate tuna (*Auxis thazard), wahoo (Acanthocybium solandri), opah or moonfish (Lampris guttatus*), bluefish (*Pomatomus saltatrix*), stripped bass (*Centropomus spp.*), dusky grouper (*Epinephelus marginatus* and others), Atlantic goliath grouper (*Epinephelus itajara* and others), flounder (several species), Atlantic promfret (*Brama spp.*), red porgy (*Pagrus pagrus*), crucifix sea catfish (*Sciades proops*), among others (Dias-Neto and Dias, 2015).

Other species such as white marlin (*Tetrapterus albidus*), Atlantic sailfish (*Istiophorus albicans) and Atlantic blue marlin (Makaira nigricans*) are important for sport fishing. Due to the critical situation of stocks, they face restrictions on commercial fishing, as recommended by the International Commission for the Conservation of Atlantic Tunas – ICCAT (Dias-Neto and Dias, 2015). Therefore, they should also be part of environmental monitoring programs when they occur in areas of RME systems.

Research related to the interaction of fish with RME devices has mostly taken place in the United States, Canada and the United Kingdom, in the temperate zone of the Northern Hemisphere. It was expected that few species would occur in Brazil, as much of its territory is in the tropical zone. Only two species of shark/dogfish were found in Brazilian waters: porbeagle (*Lamna nasus*) and picked dogfish (*Squalus acanthias). Porbeagles occur off the southern coast of Brazil and are often found in groups in both coastal and oceanic waters up to 1 800m deep (Silveira, 2020). In Brazil, the porbeagle (Lamna nasus*) was not considered endangered (EN), being classified as insufficient data (DD). The picked dogfish (*Squalus acanthias*) is restricted to the coast of the southern region of the country and occurs sporadically in the states of Santa Catarina and Rio Grande do Sul. It is a demersal specie of cold and temperate waters, occurring on the continental shelf and higher slope. Picked dogfish was considered critically endangered (CR) in the country, with a declining population trend, and is included in the National Action Plan for the Conservation of Endangered Sharks and Marine Rays (ICMBio, 2018). Although studies carried out near the Bay of Fundy, Maine (USA) and Nova Scotia (Canada) do not assess the specific interaction of these animals with RME devices, these works are reference for future studies and environmental monitoring of marine energy projects that may be installed in the south of the country, where porbeagles and picked dogfish occur.

4.3 Seabirds

Seabirds are those that depend on the resources existing in marine environments for their survival, being highly adapted to live in the sea (Branco, 2004). They spend most of their lives moving across the oceans, remaining on land only for breeding. They can also be called oceanic or pelagic birds.

Table 2. Marine fish economically important for Brazil (Source: Dias-Neto and Dias, 2015).

Species or species groups	Common name	Fishing area / Habitat	Average production for the period 1995 to 2010 (tons)	Use status / source
Sardinella brasiliensis	Brazilian sardine	Southeast and South. It inhabits coastal waters, entering bays and estuaries. It is found between 30 and 100 meters deep.	56 334	Overexploited
Micropogonias furnieri	Whitemouth croaker	Southeast and South, but it is also found along the entire Brazilian coast. It is a coastal demersal species, associated with freshwater mouths.	28 319	Overexploited
Opistonema oglinum (Atlantic thread-herring), Harengula jaguana (scaled sardine) and others.	Other sardines (Atlantic thread-herring, scaled sardine and others)	Brazil. They inhabit coastal areas and usually form schools.	21 842	Fully exploited
Katsuwonus pelamis	Skipjack tuna	Southeast and South. They occur in oceanic areas, therefore, are exploited by industrial fishing.	23 449	Fully exploited
Thunnus obesus (bigeye tuna), *Thunnus alalunga* (albacore), *Thunnus albacares* (yellowfin tuna)	Other tuna (albacore, bigeye tuna and yellowfin tuna)	Brazil. They occur in oceanic areas, therefore, it is exploited by industrial fishing.	19 520	Full / in recovery
Cynoscion acoupa	Acoupa weakfish	North and Northeast, but occurs along the entire Brazilian coast. It has demersal and coastal habits, in shallow and brackish waters of estuaries and river mouths.	16 981	Fully exploited
Mugil spp.	Mugil	Brazil. Species with wide distribution, occurring in coastal, marine and estuarine waters.	13 623	Fully exploited
Species of the Ariidae family.	Catfish	Brazil. Most of the species occur in coastal areas, shallow, with muddy or sandy bottoms.	10 669	Fully exploited
Umbrina canosai	Argentine croaker	Southeast and South. Demersal species, occuring in coastal and marine areas.	9 969	Overexploited
Several species	Dogfish / sharks	Brazil. The vast majority of species are considered predators and occupy pelagic, demersal, abyssal, coastal, estuarine or freshwater environments.	9 946	Fully exploited
Scomberomorus brasiliensis	Serra Spanish mackerel	Brazil. They have pelagic behavior and a more coastal geographic distribution, being caught in small-scale fisheries.	9 883	Fully exploited
Sciades parkeri (VU).	Gillbacker sea catfish	North. It is a demersal species, found in estuaries and coastal waters up to 20 meters deep in northern Brazil, and can also be found in fresh water.	7 749	Fully exploited
Cynoscion guatucupa	Stripped weakfish	Southeast and South. In southern Brazil, they occur in coastal waters, generally at depths below 50 m, but specimens have already been captured at 150 m.	7 180	Overexploited
Lutjanus purpureus (VU)	Southern red snapper	North and Northeast. It is a marine demersal species, from tropical reef environments, occurring at depths from 26 to 340 m.	6 281	Overexploited
Macrodon ancylodon	King weakfish	North and Northeast. Demersal fish found in shallow coastal waters, in sand and mud bottoms, occurring at depths of 30 to 70 m.	5 753	Fully exploited
Urophycis brasiliensis	Brazilian codling	Southeast and South. Inhabits shallow coastal waters up to 190 m deep. Adults are close to the bottom, while young people are pelagic.	4 427	Fully exploited
Macrodon ancylodon	King weakfish	Southeast and South. Demersal fish found in shallow coastal waters, inhabits sand and mud bottoms, occurring at depths of 30 to 70 m.	4 064	Overexploited
Lophius gastrophysus	Blackfin goosefish	Southeast and South. It is a fish that inhabits the continental shelf and the upper slope, with reduced mobility, and is found between 40 m and 620 m in depth.	2 221	Overexploited

In Brazil, there are 13 taxa (species and subspecies) threatened with extinction according to the National Action Plan for the Conservation of Seabirds - PAN Aves Marinhas (Table 3), approved by Ordinance MMA/ICMBio No. 286, of 4 April of 2018.

In addition to these taxa, *Procellaria aequinoctialis* (white-chinned petrel), *Procellaria conspicillata* (spectacled petrel), *Thalassarche chlororhynchos* (Atlantic yellow-nosed albatross), *Diomedea epomophora* (Southern royal albatross), *Diomedea sanfordi* (Northern royal albatross), *Diomedea exulans* (wandering albatross), and *Diomedea dabbenena* (Tristan's albatross), of the Procellariiformes order, deserve attention in the assessment of the risk of collision, as they are seabirds and appear in the red book of endangered Brazilian fauna, despite not being included in the priority conservation strategies of the PAN Aves Marinhas. These birds occur mainly in the south and southeast of Brazil.

Of the species studied to assess the risk of seabirds colliding with RME devices, only the common tern (*Sterna hirundo*) and the Arctic tern (*Sterna paradisaea*) occur in Brazil. Lieber *et al*. (2019) observed in Northern Ireland that these species preferred to forage in device wake locations, which may increase the risk of collision with turbulent structures (shallow pinnacle at 5 m depth) as they forage close to the surface. Jackson *et al*. (2014) found that Arctic terns used floating wave energy devices to rest and potentially forage, which could increase the risk of collision. Thus, studies aimed at evaluating the stressor-receptor interaction of these species in the country already have data to be compared.

The neotropic cormorant (*Nannopterum brasilianus*), traditionally found in Brazil, is considered to be of the *Phalacrocorax* genus. Kennedy and Spencer (2014), however, showed that neotropical species, including the Galapagos Islands, belong to distinct clades and should be recognized in another genus (Piacentini *et al*., 2015), which makes the European shag (*Phalacrocorax aristotelis*), studied in Scotland, United Kingdom, a different specie of cormorant.

Table 3. Endangered bird taxa according to the PAN Aves Marinhas (Source: ICMBio, 2018).

Order	Species	Common name	Category of extinction risk / Geographical distribution in Brazil
Suliformes	*Sula sula*	Red-footed booby	Endangered (EN). In Brazil, it occurs in Fernando de Noronha, Atol das Rocas and the São Pedro and São Paulo archipelago. Strictly pelagic.
Suliformes	*Fregata ariel*	Lesser frigatebird	Critically endangered (CR). Occurrence of the subspecies *Fregata ariel trinitatis*, restricted to the islands of Trindade and Martin Vaz, in Espírito Santo, inhabits tropical and subtropical seas.
Suliformes	*Fregata minor*	Great frigatebird	Critically Endangered (CR). Occurrence of the subspecies *Fregata minor nicolli* on the islands of Trindade and Martin Vaz, Espírito Santo, inhabits tropical and subtropical seas.
Phaethontiformes	*Phaethon aethereus*	Red-billed tropicbird	Endangered (EN). Occurrence only of the subspecies *Phaethon a. aethereus*, with reproduction in Abrolhos and Fernando de Noronha. There are occasional records on the coast of Maranhão, Atol das Rocas, north and south of Bahia. They are mainly pelagic, inhabiting tropical and subtropical seas.
Phaethontiformes	*Phaethon lepturus*	White-tailed tropicbird	Endangered (EN). Occurrence in Abrolhos and Fernando de Noronha, also breeding sites. They are mainly pelagic, inhabiting tropical and subtropical seas.
Procellariiformes	*Pterodroma madeira*	Zino's petrel	Endangered (EN). There are records, by geolocators, on the coast of northeastern Brazil, a probable wintering area. Pelagic species.
Procellariiformes	*Pterodroma deserta*	Desertas petrel	Critically Endangered (CR). Overwintering areas between the coast of Ceará and Pernambuco, Espírito Santo and north of São Paulo. Pelagic species.
Procellariiformes	*Pterodroma incerta*	Atlantic petrel	Endangered (EN). Regular occurrence in waters adjacent to the south and southeast coast of Brazil, but there are records in the North and Northeast regions. Pelagic species.
Procellariiformes	*Pterodroma arminjoniana*	Trindade petrel	Critically endangered (CR). It takes place on Trindade Island, in Espírito Santo. Highly pelagic species, rarely approaching land.
Procellariiformes	*Puffinus lherminieri*	Dusky-backed shearwater	Critically endangered (CR). In Brazil, it only reproduces on two islands of Fernando de Noronha. Pelagic species.
Charadriiformes	*Sterna dougallii*	Roseate tern	Vulnerable (VU). There are records of passage in the Southeast, Northeast and North, but the wintering area occurs only in Bahia.
Charadriiformes	*Sterna hirundinacea*	South American tern	Vulnerable (VU). Largest records occur from Espírito Santo to Rio Grande do Sul. It nests in Brazil and is almost exclusively coastal.
Charadriiformes	*Thalasseus maximus*	Royal tern	Endangered (EN). Largest records occur from Espírito Santo to Rio Grande do Sul, but there are occurrences in the North and Bahia. It nests in islands of São Paulo. Inhabits coastal areas.

It is advisable that international studies be carried out in Brazil, even with common species and similar devices, when installation, operation and decommissioning of RME systems occur, as species tend to have behavioral variations (foraging and diving) in different locations. The search for local research in the region of the project should also be considered, so to obtain behavioral data on the species to be applied in the collision risk models.

4.4 Marine reptiles

The Reptilia class has some marine species of the orders Squamata, Crocodylia and Testudines. In Brazil, marine reptiles are represented by 5 of the 7 species of marine turtles (Table 4) existing in the world (Sforza *et al*., 2017). Belonging to the Testudines order, sea turtles use estuaries and/or oceans in their life cycle (Santos, 2021b). Sea turtles have great ecological importance, due to the cycling of energy and nutrients between different environments, in the control of the species they feed on and as a food source for crustaceans, birds, fish and mammals, although their predators are more restricted in the adult phase (Bjorndal, 1997).

Most of the world's sea turtles (*Caretta caretta, Chelonia mydas, Dermochelys coriacea, Eretmochelys imbricata, Lepidochelys olivacea, Natator depressus and Lepidochelys kempi*) are threatened with extinction, except for *Natator depressus* (Salvarani *et al*., 2013). The decline of populations is associated with human activities on their habitat, such as incidental capture through the use of different fishing gears and pollution by solid waste, which can hinder female access to the spawning site (compromising reproductive success) and become food (Mascarenhas *et al*., 2008), and climate change, due to the role of temperature in determining the sex of embryos. A 2°C increase in sand temperature can lead to the feminization of the entire population (Salvarani *et al*., 2013).

The life cycle of sea turtles is long and has a wide geographic distribution between feeding and reproduction areas, in a marine environment, and spawning sites, in a terrestrial environment. The sexual maturation of sea turtles varies between 10 and 50 years, depending on the species. For example, the maturation of *Chelonya midas* can range between 25 and 50 years (Sforza *et al*., 2017). These characteristics (late maturation, long life cycle and migratory behavior) imply a slow population replacement capacity which, added to anthropic actions, make sea turtles vulnerable species and, therefore, the target of various protection programs and projects. In Brazil, several federal, state and municipal marine and coastal protection areas were created to protect these species, such as the National Marine Park of Fernando de Noronha-PE and the Biological Reserves of Atol das Rocas-RN, of Santa Isabel-SE, and Train-ES (Sforza *et al*., 2017).

Based on the above, sea turtles are vulnerable to marine developments and, therefore, were included in this list of priority species for monitoring RME systems. Even though there are no studies that monitor the interaction of these animals with EMR devices in Copping *et al*. (2020). This fact agrees with Sforza *et al*. (2017), who developed a guide with information on areas of relevance for the conservation of turtles, in order to guide entrepreneurs, environmental agencies, consultants and researchers involved in the environmental licensing process in these areas. The publication attests the potential impacts of the implementation and operation of the main types of enterprise, with an indication of mitigation and monitoring measures. However, marine energy projects were not analyzed by Sforza *et al*. (2017), but due to damage caused by other

Table 4. Species of sea turtles from Brazil (Source: ICMBio, 2018).

Family	Species	Common name	Category of extinction risk / Geographical distribution in Brazil
Cheloniidae	*Caretta caretta*	Loggerhead turtle	Endangered (EN). Occurrence of individuals between Pará and Rio Grande do Sul, in coastal or oceanic areas. Priority spawning areas: north coast of Rio de Janeiro, Espírito Santo, north of Bahia and Sergipe.
Cheloniidae	*Chelonia mydas*	Green sea turtle	Vulnerable (VU). They are registered throughout the Brazilian coast and show more coastal habits. Priority spawning areas: Ilha da Trindade (ES), Atol das Rocas (RN) and Fernando de Noronha (PE).
Cheloniidae	*Eretmochelys imbricata*	Hawksbill turtle	Critically endangered (CR). Occurrence throughout the Brazilian coast. Priority spawning areas: northern Bahia and the state of Sergipe; and south of Rio Grande do Norte.
Cheloniidae	*Lepidochelys olivacea*	Olive ridley turte	Endangered (EN). Occurrence records throughout the Brazilian coast. Priority spawning areas: north of Bahia to the south coast of Alagoas.
Dermochelydae	*Dermochelys coriacea*	Leatherback turtle	Critically Endangered (CR). Occurrence records throughout the Brazilian coast. Priority spawning area: north coast of Espírito Santo.

types of projects (collision with tourist or industrial vessels, with rocky blocks in the construction of breakwaters and rockfall in coastal works, and entanglement by garbage, which make them more susceptible to collision with vessels), sea turtles must be included in research on the risk of collision with RME systems in what concerns the following behavior patterns: (1) evasion or attraction, (2) migration from preferred locations, and (3) vertical distribution in the water column due to the flow generated by turbines.

5. CONCLUSIONS

The pressing need to reduce greenhouse gas emissions to slow global warming is the driving force behind the development of the renewable energy sector. Brazil's potential to develop marine renewable energy systems touches upon the discussion about the environmental impacts of these technologies on ecosystems. The risk of collision of marine animals such as mammals, fish and birds is a factor of concern for the environmental monitoring of international RME projects.

The surveys evaluated did not record the occurrence of collisions with marine animals, which does not mean that they did not occur, but that they may not have been registered, due to the limitation of implemented projects and the significant challenges of monitoring. Furthermore, some studies have great data uncertainty. These factors allow gaps in knowledge of RME collision risk.

The integration of research from the fields of engineering, technology and biology is a solution, both for improving the understanding of the risks of collision of marine animals and for reducing this risk. Improving the knowledge of the risk of collision of marine animals can reduce barriers in the consent of RME projects, by adopting conservative levels of risk of collision, without considering the parameter of evasion of animals, preventing the development of the marine renewable energy sector in the world. In the review, no studies were identified with sea turtles, an animal that is the target of several environmental conservation projects in Brazil and with a strong influence on environmental conditions. Only four species, two of fish (*Lamna nasus* and *Squalus acanthias*) and two of birds (*Sterna hirundo* and *Sterna paradisaea*) occurring in the country were found in the analyzed studies, revealing the little knowledge of the interaction of Brazilian marine fauna with RME devices.

The need for future studies, even on prototypes or individual equipment, is essential to assess the potential risks of collision and other impacts of marine animal portrayed in this article (underwater noise, electromagnetic fields, mooring entanglement and changes in habitat). Therefore, fostering the development of these RME systems in the country is essential. Towards a future with zero GHG emissions, this article provides information for entrepreneurs, researchers and environmental agencies involved in environmental licensing, by indicating priority species for monitoring the interaction and risk of collision with RME devices in Brazil, with information on geographic distribution, habitats and extinction risk category or exploitation status necessary for environmental impact studies.

CONTRIBUTIONS

Catarina Luiza Damasceno Lima da Silva: Study design, methodology development, data collection and analysis, and manuscript writing.

Luís Felipe Umbelino dos Santos: Conception of the study, review of data analysis, suggestions and study advisorship, writing of the manuscript.

Marcos Antônio Cruz Moreira: Conception of the study, review of data analysis, suggestions and study advisorship, writing of the manuscript.

Pedro Henrique Castello Branco Dágola: Data analysis, work suggestions, writing and translation of the manuscript.

All authors contributed to the writing (reviewing and editing) of the manuscript.

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LONG-TERM COASTLINE EVOLUTION OF FIGUEIRA DA FOZ – NAZARÉ SECTOR (PORTUGAL)

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ABSTRACT: Some sectors of the west Portuguese coast are particularly endangered by erosion and flooding. Regional to local scale information, on coastline evolutionary trend, is particularly valuable in sectors that includes areas with relevant erosion. A continuous, high-resolution, dataset on coastal evolution, from 1947 and 2015, between *Figueira da Foz* and *Nazaré*, was achieved within the Programme "Geological and Coastal Hazard Mapping at a 1:3000 resolution scale" at the National Laboratory of Energy and Geology (LNEG).

This work, due to the detailed scale of analysis in a wide geographic context, allows to have both, a general overview of the coastal evolution and, at the same time, when zooming in up to 1:3000 scale, to observe the local behaviour and to quantify the occurred changes. Also, the well time-spaced aerial photograph dataset allows to compare the resultant coastline movement between the oldest and the youngest coastline (NSM index), with the total coastline oscillation (SCE index), bringing new insights on the coastline stability at a local scale.

The evolution trend shows an overall erosional behaviour, if considering the entire sector. Erosion occurs predominantly in the north, as the south shows more stability and progradation. Quantification of the land-lost and land-gain due to the coastline shift in a 68-year period shows that 1 164 888 m^2 of land were lost along 30 470 m of the coastal fringe, and 462 330 m^2 were gained along an extension of 21 010 m.

Keywords: Coastal hazard mapping; Western Portuguese coast; Coastline evolution; Coastal erosion and accretion; Digital Shoreline Analysis System (DSAS).

RESUMO: *Alguns sectores da região oeste da costa portuguesa estão particularmente ameaçados por fenómenos de erosão costeira e inundação. A informação sobre a tendência evolutiva da linha de costa, a uma escala regional e local, é particularmente importante em sectores onde se verifica erosão costeira relevante. Dados contínuos, de alta resolução, sobre a evolução da linha de costa entre 1947 e 2015, no sector costeiro entre a Figueira da Foz e a Nazaré, foram produzidos no Laboratório Nacional de Energia e Geologia (LNEG) no âmbito do Programa "Cartografia Geológica e de Perigosidade da Zona Costeira, à escala 1:3000".*

Este trabalho, devido à análise realizada a uma escala de grande detalhe, permite ter uma visão geral da evolução da linha de costa deste sector e ao mesmo tempo, ampliando à escala 1:3000, observar o seu comportamento bem como quantificar as mudanças ocorridas em pequenas áreas. Além disso, a análise de um conjunto de dados de fotografias aéreas, espaçadas no tempo, permite comparar a evolução da linha de costa entre o período mais antigo e o mais recente (índice NSM), com a oscilação total da linha de costa (índice SCE), trazendo um novo conhecimento sobre a sua estabilidade a uma escala local.

A tendência evolutiva mostra um comportamento erosivo global, se considerado todo o sector analisado. No entanto, a erosão ocorre predominantemente no sector norte, sendo que a zona sul apresenta mais estabilidade e progradação. A quantificação da perda e ganho de território devido às variações da linha de costa durante os últimos 68 anos mostra que se perderam 1 164 888 m^2 de território ao longo de 30 470 m da orla costeira, havendo um ganho de 462 330 m^2 ao longo de uma extensão de 21 010 m.

Palavras-chave: Cartografia de perigosidade costeira; Litoral português oeste; Evolução da linha de costa; Erosão costeira; DSAS.

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1. INTRODUCTION

The coastline of the Portuguese mainland extends approximately along 900 km, having a wide morphological diversity and comprising a multiple range of environments, being the beaches, wetlands, hardened and cliffed coasts the main typologies.

As ¾ of the population live in the coastal areas, generating around 80% of the gross national product, this sector has a considerable economic importance (Santos and Miranda, 2006). Moreover, worldwide, but particularly in Portugal, coastal environments are critically endangered by flooding and erosion, which will be expectedly intensified by the climate change effects, consequently placing more emphasis on the need of an urgent holistic approach to a successful adaptive coastal governance (Taveira-Pinto et. al., 2021, Vousdoukas *et al.*, 2020; Schmidt *et al.*, 2013, Coelho et. al., 2009).

The achievement of updated and reinterpreted regional to local-scale information, on long-term coastline evolutionary trend, is particularly valuable in areas with relevant erosion as the safety measures to apply in those sectors should be strongly supported and backed by scientific information. That is the case of the centre of Portugal western coast, as shown in previous studies, which is significantly endangered by erosion, with average values of rate of change, varying between - 0.19 and - 0.91 m/year (Lira *et al.*, 2016).

In order to refine and contribute to the knowledge of this peculiar coastal sector, a high-resolution coastal evolution assessment of the sandy coastline sectors from *Figueira da Foz* to *Nazaré*, for a 68-year period and with an approximately 10-year interval, has been determined within the Programme "Geological and Coastal Hazard Mapping at a 1:3000 resolution scale" of the National Laboratory of Energy and Geology (LNEG) (Nave and Rebêlo, 2018). It is expected that the produced dataset constitutes a valuable tool and a contribute to support coastal managers and users of littoral regions.

2. REGIONAL SETTINGS

The western Portuguese coastline is fully exposed to the strong energetic marine wave climate, which, in combination with an NNW-SSE orientation, is powered by a high magnitude of potential of longshore drift (of the order of 10^6 $m^3 year^{-1}$) (Santos *et al.*, 2014).

According to the geomorphological characteristics and sedimentary dynamics cells that characterize the continental Portuguese coastal classification (Andrade and Freitas, 2002; Santos *et al.*, 2014), which divides the coast in 8 cells, the study area (figure 1) is located at the western side within the designated first cell (which extends from the mouth of the river *Minho* to *Nazaré*). Cell 1 was, in turn, divided into 3 sub-cells: from *Minho* to Douro (1a), from Douro to Cape *Mondego* (1b) and Cape *Mondego* to *Nazaré* (1c) (Santos *et al.*, 2014), being the last sub-cell extent, the focus of the current work. The intense and growing human activity on the coast, and also on hydrographic basins, has led to a sharp reduction in the sedimentary supply (Veloso-Gomes et. al., 2004, Oliveira *et al.*, 1982;), to which was associated an erosion tendency of specific segments of this cell, namely *Espinho - Furadouro*, *Costa Nova - Mira* and *Cova Gala - Leirosa*.

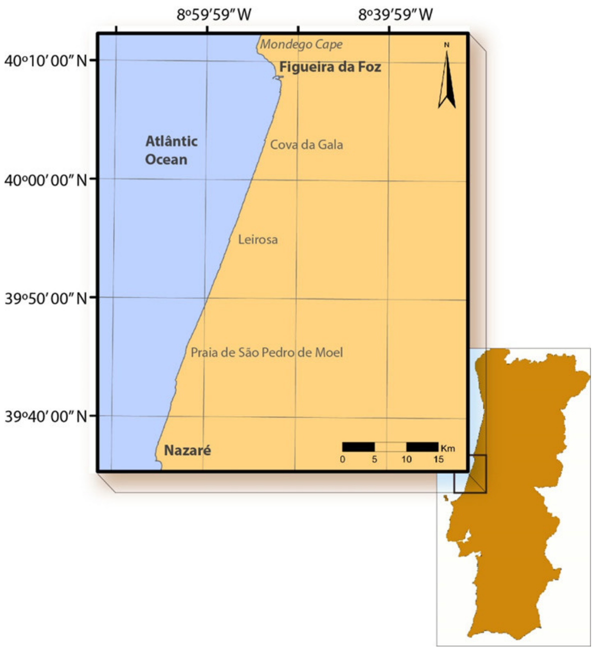

Figure 1. Study area: the western Portuguese coastal sector from *Figueira da Foz - Nazaré* (sedimentary sub-cell 1c).

The *Figueira da Foz - Nazaré* littoral sector comprises, mainly, three types of environments: low-lying beaches, where 72 % of them are backed by dunes (Lira *et al.*, 2016), hardened coasts and cliffed shores, bordered, or not, by narrow beaches.

Although showing an apparent continuity, a diverse coastal geology plays an important role in coastal processes and hence, in the different existent coastal morphologies.

At Cape *Mondego*, the coast is rocky, with cliffs and a marine abrasion platform carved mostly in limestones, passing progressively to a sandy beach, which become extremely wide, north of the *Mondego* River, due to the sand retention on the northern breakwater of the *Figueira da Foz* harbour (Santos *et al*., 2014).

From the *Mondego* River mouth to *São Pedro de Moel*, a straight low-lying sandy coast prevails, with wind-blown sand migrating inland. A foredune or, more rarely, a sequence of foredunes, backed by an extensive transgressive dunefield is the most common geological setting. Rivers play a local role in shaping the coastline and its change. In some sectors a morphological depression between these two different dune systems exists, which favours the marine intrusion when the foredune ridge is eroded. Some foredunes ridges are related with fences, deployed in the recent past as sand traps. Those structures are presently visible in the actual dune erosion scarps and are a good indicator of coastline retreat.

São Pedro de Moel plays nowadays an important role in the coastline evolution for several reasons: (1) it acts as a natural groin, anchoring the shore position and promoting updrift accumulation; (2) south of this locality the coast is dominated by a rocky shore; (3) south of this point the higher altitude of the bedrock, if compared with the northern sector, gives rise to a cliff coast bordered by a narrow beach and (4) the effect of a slightly northward orientation of the coast, induces a small increase in the potential of the coastal drift (Santos *et al*., 2014), which may contribute, in some sections, to the presence of a small beach, limited by cliffs and promontories. Although the transgressive dunes continue to exist as a top cliff dunefield, the continuity between beach and the dunefield is generally interrupted as a result of a smaller sediment availability. Aeolian ramps and climbing dunes, which allows the inland sand migration, are only visible at the south of the study area, north of the *Nazaré* promontory (an approximately 3,7 km coastal stretch), as a result of sand accumulation against the natural cliff, even in scarce sedimentary periods, as presently.

The two main sources of sediments to this sector (sub-cell 1c) are related with the Cape *Mondego* sediment bypassing and the *Mondego* River sediment discharge. The sediments that cross the *Mondego* Cape are transported southward along *Buarcos* beach to *Figueira da Foz* beach. Here, its natural course is conditioned by the northern breakwater of the *Mondego* River, which promotes a sedimentary retention northward that structure, causing the observed exceptional growth of *Figueira da Foz* beach from 1960 to 1980 (Dias *et al*., 1994 in Santos *et al*., 2014). These promoted coastal morphology and river flow changes, alongside with the updrift sediment retention, induced a noticeable retreat of the coastline southward, on the *Cova Gala - Pedrogão* section, which led, as a safety measure, to the construction of a set of rigid coastal protection structures. As result of a new 400 m expansion of the north jetty, that occurred between 2008 and 2010, there was a new increase in the northern beach width, exceeding 500 m. This increased retention reinforced, once again, the previously installed erosive trend on the southward sectors, especially at *Cova Gala*, *Lavos* and *Leirosa*, which likely extends even further south (André and Cordeiro, 2013).

As a result of the observed erosive process, mitigated by the dredging promoted by the port with sediment deposition near shore of *Cova Gala*, it is estimated that the sedimentary transposition is slightly more than half of the potential drift (6×10^5 $m^3 year^{-1}$) (Santos *et al*., 2014). However, following the saturation of the north jetty, it is expected that the volume of sediments that (naturally and artificially) cross the inlet tends to increase, reducing the observed severe erosion process.

The southern limit of the study area, which coincides with southern limit of the cell 1c, is characterized by two major morphologic features that have a major influence in the littoral drift: the *Nazaré* promontory and the *Nazaré* canyon.

The *Nazaré* promontory acts like a natural groin and is responsible for an updrift sand accumulation. The *Nazaré* canyon, that extends from a water depth of 50m near the Portuguese coast to 5000 m at the edge of the Iberian Abyssal Plain. Even though the canyon constitutes a giant sedimentary sink, its influence on sediment transport is up to the beach (Beach to Canyon (2013). Actually, the canyon system is not draining sediments from a modern river obtaining, instead, its present-day sediment input by capturing of along-shelf sediment transport and depositing much of it in the middle canyon, between about 2700 and 3800 m (Masson *et al*., 2011). Thus, most of the sand transported southward in the coastal drift (11×10^5 $m^3 year^{-1}$) is conducted, and therefore totally lost, to the deep ocean by the *Nazaré* canyon system (Santos *et al*., 2014).

3. METHODOLOGY

As the produced data intends to be comparable to the previous systematic works carried within the "*Geological and Coastal Hazard Mapping at a 1:3000 resolution scale*" programme of the National Laboratory of Energy and Geology, the used methodology is similar to the one described at Nave and Rebêlo (2021).

3.1 Coastline indicator

As the objective of the current work is to provide high-resolution quantitative data on the long-term (nearly 70 years) coastline evolution, the foredune shoreward edge was used as a marker of the coastline to exclude short-term (tidal) variations or medium-term (seasonal) variations, as described at Nave and Rebêlo (2018) and references therein. In cliff areas, the position of the coastline was marked using the boundary of the cliff base (Rebêlo and Nave, 2019).

The continuous coastline position was smoothly depicted at the maximum scale of 1: 800 to undoubtedly identify the outer limit of the dune zone. Interruptions in the vegetation line of less than about 150 m were not considered, maintaining in this case the continuity of the line between adjacent segments. In the case of settlements or large infrastructures that hindered the expansion of the dune field, the continuity of the line between adjacent segments of the interruption was also considered (Rebêlo and Nave, 2019).

In order to determine the error inherent to the operator, for each year, the coastline was marked by two different operators using the same criteria. The coastline used for each year thus corresponds to the average position of the lines calculated between the two operators (Rebêlo and Nave, 2019).

3.2 Data sources

Aerial photographs and ortophotomaps from nine different years (1947, 1958, 1973, 1980, 1982, 1988, 2004, 2010 and 2015) were used in order to achieve a near-decadal analysis. The data was provided by Direcção Geral do Território and by CiGeoE (Army Geospatial Information Center). The non-digital aerial photos were scanned at 2400 dpi and then, mosaics were made, using the Adobe Photoshop CS6 image software. This was done with the aim to expedite the georeferencing process, since it allows to avoid marking duplicated links in the overlap area between two consecutive aerial photos (Rebêlo and Nave, 2019).

Additionally, given that the link creation process on the scanned image leads to uncertainties of magnitude similar to the accuracy of the images, the use of mosaics also reduces georeferencing errors. The georeferencing process was accomplished using ESRI software, ArcMap, from ArcGIS Desktop 10.6.1, based on the 2015 orthophotomap as reference map (the most recent one available at the date this work was done). Since the objective was the digitization of the coastline, this process had a greater focus on the area next to the coastline, with increased control points density close to it. Those points were marked, using the Spline interpolation method, preferably with a zoom, at the scale of the order of 1: 400, 1: 600 or, at most, 1: 800 (Rebêlo and Nave, 2019).

3.3 Mapping procedures and DSAS calculation of coastline evolution

After determination of the average coastline position for each of the nine historical aerial photographs, coastline evolution was calculated using the Digital Shoreline Analysis System (DSAS) Software, that is an add-in within the Environmental System Research Institute (ESRI) ArcGIS© ArcGIS desktop v. 10.4-10.6. It, thus, enables a user to calculate a range of statistical change measures derived within DSAS, based on the comparison of coastline positions through time (Himmelstoss *et al*., 2018); (https://www.usgs.gov/centers/whcmsc/science/digital-shoreline-analysis-system-dsas?qt-science_center_objects=0#qt-science_center_objects).

For this work, DSAS allowed us to calculate coastline rate-of-change statistics based on the measured differences between nine coastline positions associated with analysed time periods (1947, 1958, 1973, 1980, 1982, 1988-90, 2004, 2010, 2015), producing three parameters:

(i) *Shoreline Change Envelope* (SCE), which is the measure of the total change in coastline movement considering all available coastline positions and reporting their distances, without reference to their specific dates;

(ii) *Net Shoreline Movement* (NSM), corresponding to the distance between the oldest (in this case, 1947) and the youngest coastline (2015). For the present work the NSM refers to an overall time-frame of 68 years;

(iii) *Linear Regression Rate* (LRR), which is a statistical parameter, that determines a rate-of-change by fitting a least square regression to all coastlines at a specific transect.

Calculations were done using 10 m spaced transects, generated perpendicular to the coast, and the results are represented as a graphic and plotted as a histogram. The coloured histogram, represents two DSAS parameters simultaneously, allowing a fast perception of the coastline evolution over time. The bar length indicates how much the coastline has shifted during the period of analysis (SCE parameter), and the bar colour indicates the NSM and LLR, with the colour (green, yellow, and red) being associated with the evolutionary trend of the coastline. The green scale stands for sectors in accretion and the yellow and red ones, for the sectors in erosion. The absolute value of this variation is shown in the legend of each figure. Due to the scale of the figures presented in the manuscript, the bar length variations are difficult to distinguish. However, they are very well visible at online LNEG GeoPortal, where zoom favours both, the bar length and colour variation perception.

Combining both variables visually, the user may rapidly deduce if, although the coast today is in the same or similar position than it was in the past, it has changed over time, and how much it has changed, in absolute value.

The calculation of the uncertainty of the coastline position, for each year, was determined according to Fletcher *et al*. (2003), where the Uncertainty (U) is the result of the square root of the sum of the squares of the errors associated with 3 parameters (Resolution of the aerial photo image (E_{ir}), Image rectification (E_r) and Digitization of the coastline (E_d):

$$U = \sqrt{E_d^2 + E_r^2 + E_{ir}^2}$$

The component associated with the coastline digitization (E_d) procedure, for each year, was determined with DSAS using the two coastline lines marked by the two different operators for each analysed year. The image resolution, E_{ir} parameter, corresponds to the pixel resolution of aerial / orthophotographs. Given that for the rectification procedure (E_r parameter), the Spline interpolation method, whose associated RMS error is null, was used, the georeferencing error was estimated by using, at least, 35 control points randomly distributed across the mosaics of each flight. Thus, the rectification error (E_r) was assumed to be the average value of the error measured at all control points, for each flight, as listed in table 1.

The uncertainty associated with the overall coastline evolution (U_{ce}) during the time frame of 68 years (t), was determined using the uncertainty values (U) calculated for each year according to Fletcher *et al*. (2012):

$$U_{ce} = \frac{\sqrt{U_{older}^2 + U_{recent}^2}}{t}$$

For this sector, the overall uncertainty (Uce) associated with the variation of the coastline along 68 years is 0.06 m / year.

Table 1. Uncertainty (U) and Errors (Ed, Eir and Er) considered for DSAS calculations.

Year	E_d	E_d^2	E_{ir}	E_{ir}^2	E_r	E_r^2	U(m)
1947	2	4	0.53	0.28	3.49	12.18	4.06
1958	4.04	16.32	0.29	0.08	2.62	6.86	4.82
1973	2.49	6.20	0.2	0.04	2.91	8.47	3.84
1980	3.19	10.18	0.16	0.03	2.78	7.73	4.23
1982	2.39	5.71	0.43	0.18	3.15	9.92	3.98
1988	2.38	5.66	0.44	0.19	3.01	9.06	3.86
2004	1.45	2.10	0.5	0.25	3.54	12.53	3.86
2010	1.41	1.99	0.5	0.25	2.18	4.75	2.64
2015	1.38	1.90	0.5	0.25	0	0	1.47

3.4 Coastline oscillation index (CO)

The ratio between the absolute value of the *Net Shoreline Movement* (NSM), which represents the resultant movement of the coastline during the time-period of analysis, and the *Shoreline Change Envelope* (SCE) value, which gives the maximum length of coastline displacement during the same period of time (Absolute value of [NSM/SCE]), is an index that, when used in comparison with the NSM, may indicate the importance of the coastline oscillation in a particular place, or sector, or, read in a different direction, the relative importance of the NSM in terms of the total displacement during the time-period of analysis. The CO index value should always be used and read together in comparison with the NSM.

4. RESULTS

Historical lines, *Shoreline Change Envelope* (SCE), coastal *Linear Regression Rates* (LLR) and *Net Shoreline Movement* (NSM) were determined and plotted along the *Figueira da Foz - Nazaré* coastal transect, except in areas with hardened and cliffed coasts (southward *São Pedro de Moel, Pedra do Ouro* and *Vale Furado*) (figures 2 and 3).

As previously mentioned, the colour and the length of the bar displayed on both hazard maps (figures 2 and 3) give, simultaneously, information on two DSAS parameters (SCE and LLR on figure 2 and SCE and NSM on figure 3), allowing a fast perception of the historical coastline evolution trend during the last, nearly, 7 decades. Thus, the bar length indicates how much the coastline has shifted (SCE), and the colour of the bars, NSM and LLR, stand for sectors in accretion (green scale) or sectors in erosion (yellow and red colour scale). The LRR map, represents the rate-of-change by fitting a least square regression

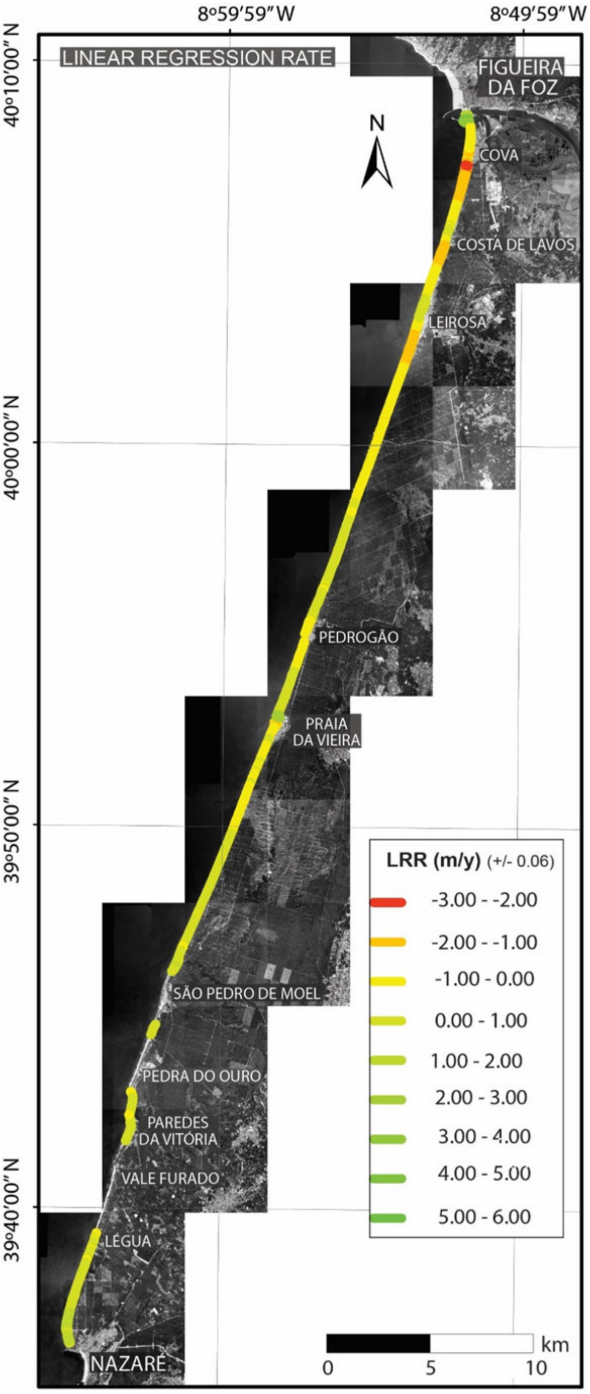

Figure 2. Linear Regression Rates (LLR) for the analysed coastal sector, between 1947 and 2015. Background photo is the 2015 ortophotomap. Map produced using ArcMap, a module from ArcGIS© Desktop 10.6.1 of ArcGIS® software by Esri.

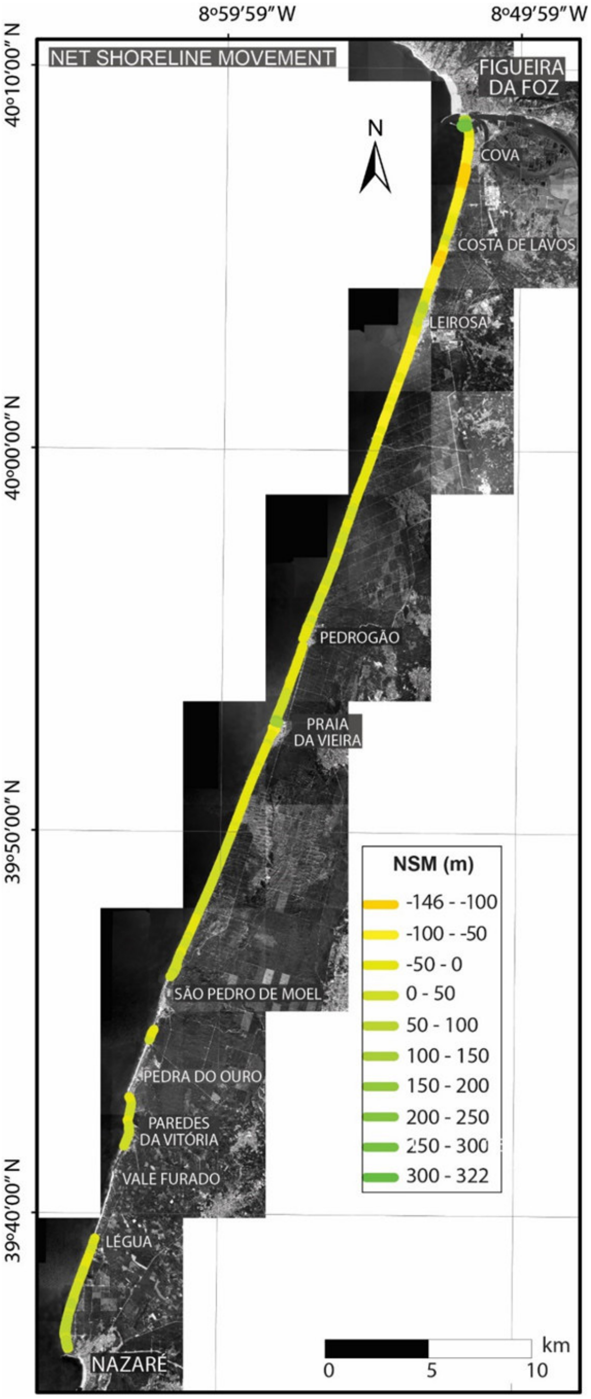

Figure 3. Net Shoreline Movement (NSM) for the analysed sector, between 1947 and 2015. Background photo is the 2015 ortophotomap. Map produced using ArcMap, a module from ArcGIS© Desktop 10.6.1 of ArcGIS® software by Esri.

to all coastlines at a specific transect (figure 2) whereas the NSM map indicates the absolute distance between the oldest (1947) and the youngest (2015) coastline position (figure 3). All the data is available as polylines with 10 m spaced resolution and openly accessible at LNEG GeoPortal [https://geoportal.lneg.pt/mapa/?escala=4000000&mapa=geologiacosteira#]. Here the produced digital data may be seen in a greater detail and combined with other available layers for this coastal sector (beach profile, sedimentary grain size distribution, photos from the beach area, geology, and others).

Coastline movement analysis, based on the NSM parameter, reveals that 2/3 of the sandy coast between *Figueira da Foz* and *Nazaré* has suffered erosion since 1947 (30.4 km of the 51.5 km total extension). The average retreat, taking only in account the sectors in erosion, is approximately 38 m, with a maximum retreat of 145 m, and the progradation, taking only in account the sectors in accretion (20.1 km in length), is approximately 22 m, with a maximum displacement of 322m. Solely one kilometre of the coastal fringe is in the same position, when compared to 1947. If the overall coastline extension is considered (51.5 Km), an average erosion of 13.5 m is obtained.

The coastline movement rate, which is expressed in this work by the LRR parameter, shows an average retreat of 0.51 my^{-1}, with a maximum value of 2.46 my^{-1}, and an average progradation of 0.43 my^{-1}, with a maximum value of 5 my^{-1} (taking only in account the respective sectors in erosion or accretion, respectively). Taking into account the total studied coastal fringe (51.5 km), the obtained results indicate an average erosion rate of 0.12 my^{-1}.

To a better reading of the DSAS parameters, the *Figueira da Foz - Nazaré* coastal stretch, fully shown in figures 2 and 3, was divided and zoomed in 9 sequential figures, and hence the detailed results, will be presented in the following sub-chapters, which division reflects merely the pragmatic circumstance of map division.

The oscillation index for each sector (table 2) was also calculated to weight the NSM value in a maximum coastline displacement context.

4.1 *Figueira da Foz – Costa de Lavos* coastal sector

This first sector, with a total length of 5860 m (figure 4), has a significant diversity in terms of coastal environments, and hence, the evolution of the coast reflects these differences.

The first subsector, with a 380 m length, is located between two groins of the *Mondego* River inlet. This coastal stretch is characterized by a strong progradation, with NSM values ranging from 86.4 to 322.1 m, and an average NSM of 198.1 m. LRR varies between 1.68 and 5.01 my^{-1}, with an average value of 3.36 my^{-1}.

Table 2. Average value of SCE, average NSM absolute value, and Coastline Oscillation index (CO): NSM absolute values / SCE ratio for the different sectors. The larger the CO ratio, the more significant is the NSM value in terms of the total coastline oscillation during the time-frame analysis.

Coastal sectors	SCE	Abs(NSM)	Abs(NSM)/SCE
Figueira da Foz - Costa de Lavos	80.0	72.8	0.9
Costa de Lavos - Osso da Baleia	71.0	60.9	0.9
Osso da Baleia	48.4	38.7	0.8
Pedrogão	50.0	12.3	0.2
Praia da Vieira	37.7	19.8	0.5
Samouco	21.9	10.4	0.5
S. Pedro de Moel	36.3	14.4	0.4
Vale Pardo - Nazaré	46.7	28.3	0.6

The second subsector corresponds to the coastal stretch directly associated to the presence of defence groins, starting after the south jetty of the *Mondego* River inlet and finishing in the fifth, and last, of the groins built to protect the *Cova* locality. This subsector, with a length of 1590 m, is characterized by erosion, with NSM values ranging from -8.38 to -88.64 m, and an average NSM of -50.79 m. LRR varies between -0.26 and -1.3 my^{-1}, with an average value of -0.62 my^{-1}.

The third subsector, extending from the last groin of *Cova Gala* to the *Costa de Lavos* groin, has a length of 3890 m. Erosion is dominant, although accretion is present in the last 300 m. NSM values ranges from -145.7 to 18.2 m and the average NSM is -68.5 m. LRR varies between -2.46 to 0.21 my^{-1}, with an average value of 0.95 my^{-1}. Considering only the erosion stretch, average NSM is -75.1 m and average LRR is -1.04 my^{-1}.

The CO [Abs (NSM)/SCE] ratio of 0.9 (table 2) indicates that the NSM values are similar to the maximum range of displacement (given by the SCE index).

4.2 *Costa de Lavos – Osso da Baleia (N)* coastal sector

This sector (figure 5) may be divided in two parts, regarding coastline retreat: The *Costa de Lavos - Leirosa* subsector and the subsector south of *Leirosa*. The first sub-sector is located between two groins and the strong erosional behaviour, southward the last *Costa de Lavos* groin, diminishes gradually and shifts to accretion as we approach the *Leirosa* groin, to the

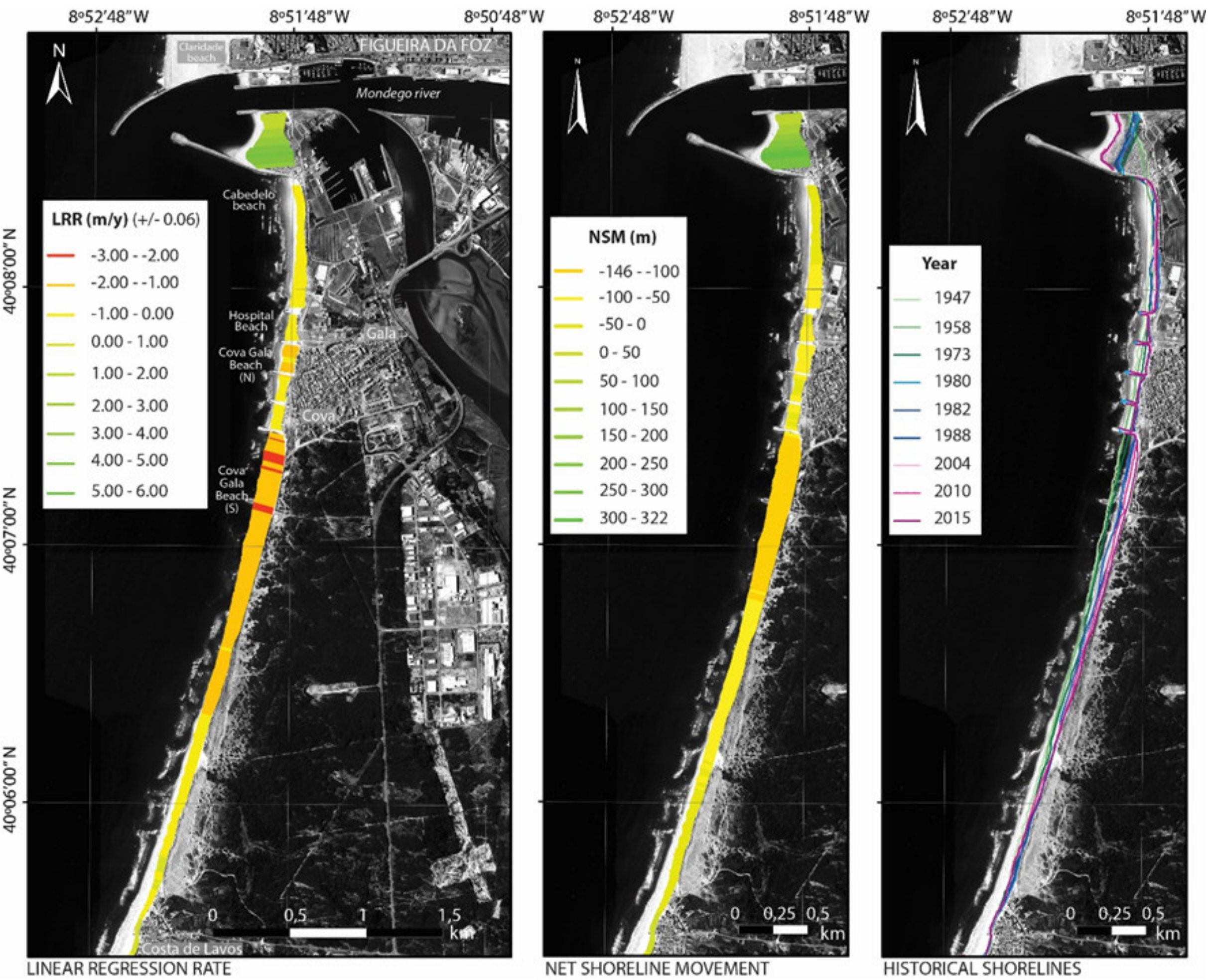

Figure 4. Historical coastline position, Linear Regression Rate (LRR) and Net Shoreline Movement (NSM) for *Figueira da Foz – Costa de Lavos* coastal sector, between 1947 and 2015. Background photo is the 2015 ortophotomap. Map produced using ArcMap, a module from ArcGIS© Desktop 10.6.1 of ArcGIS® software by Esri.

south. This sector, with 2990 m length, has an average retreat of -63 m (NSM) at a rate of 0.88 my^{-1} (LRR). The maximum retreat value found is 117.8 m at a 1.68 my^{-1} rate. The prograding coastal stretch, with 910 m length, has an average advance of 38.8 m (NSM) at a rate of 0.54 my^{-1} (LRR). The maximum offshore displacement value found has a NSM of 77.6 m with a LRR of 0.9 my^{-1}.

The 3000 m coastal stretch south of *Leirosa,* where erosion prevails, shows an average retreat of -65.1 m, at a rate of -1.04 my^{-1}. The maximum retreat, with a value of -103.7 m (and a LRR of -1.37 my^{-1}) is found approximately 1600 m south of the *Leirosa* groin.

Considering the whole sector, the 6890 m coastal strip shows an average retreat of 50.6 m with a LRR of 0.76 my^{-1}.

The CO index, [Abs (NSM)/SCE], of 0.9 (table 2) indicates, like in the previous sector, that the NSM values are similar to the maximum range of displacement (given by the SCE index).

4.3 *Osso da Baleia* coastal *sector*

In the *Osso da Baleia* coastal sector (figure 6), which has a total length of 7070 m, erosion prevails in approximately 6630 m.

Considering only the eroding sector, the average coastline retreat (NSM) is -40.7 m, reaching a maximum value of -78.4 m at a distance of 60 m from the northern sector limit. The erosion nearby *Osso da Baleia* beach has a value of -41 m. For this eroding sector LRR has an average value of -0.58 my^{-1} and a maximum value of -1.05 my^{-1}. Accretion is scarce (only 440 m of the coastal sector) and is mostly located in the south of

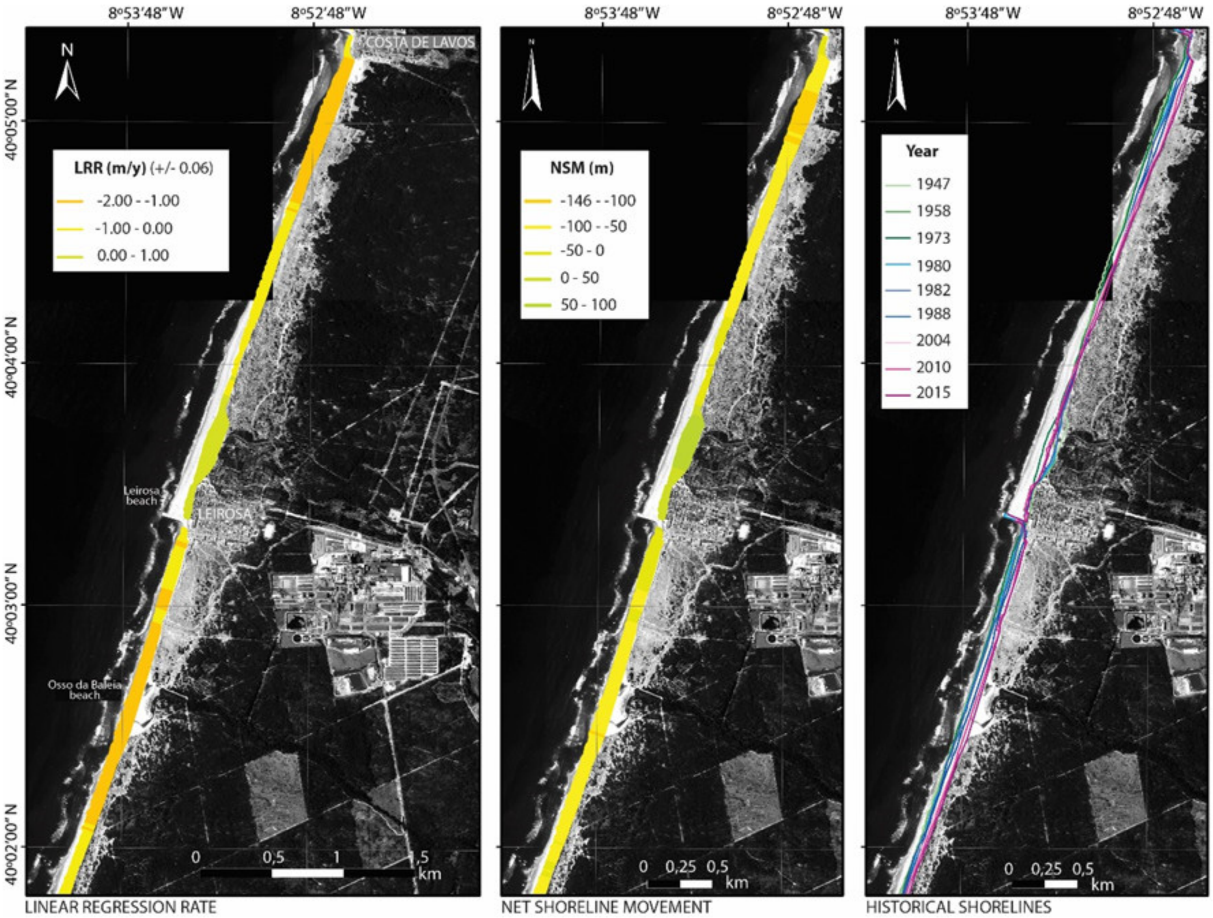

Figure 5. Historical coastline position, Linear Regression Rate (LRR) and Net Shoreline Movement (NSM) for *Costa de Lavos – Osso da Baleia* coastal sector, between 1947 and 2015. Background photo is the 2015 ortophotomap. Map produced using ArcMap, a module from ArcGIS© Desktop 10.6.1 of ArcGIS® software by Esri.

the sector. The average progradation (NSM) is 7.5 m with a maximum of 17.4 m, 230 m northward of the southern limit of the sector.

Considering the 7070 m sector length, the average coastline retreat (NSM) is -37.6 m.

The CO index, [Abs (NSM)/SCE], of 0.8 for this sector (table 2) shows a small decrease in the ratio, however, like in the previous sectors, the NSM values may be considered similar to the maximum range of displacement (given by the SCE index).

4.4 Pedrogão coastal sector

In opposition with the preceding sector, accretion prevails in this coastal stretch (figure 7), although without presenting significant values. The first 6180 m, located north of Pedrogão, shows an oscillation between eroding and accretion zones. The erosion, in terms of NSM, extends for 1680 m, while accretion covers 4500 m. The NSM ranges from -40.4 to 42.3 m, with an average accretion of 5.75 m. The LRR ranges from -0.75 to 0.66 my^{-1}, with an average rate of accretion of 0.17 my^{-1}. If considering only the positive NSM's, the progradation shore extends from 4500 of the 6180 m and has an average NSM of 11.87 m.

South of Pedrogão, erosion prevails in the small 520 m sector, with a minimum NSM value of -28.8 m and an average of -21.1 m. Average LRR is -0.39 my^{-1}, with a maximum retreat rate of -0.55 my^{-1}.

Considering the overall 6690 m sector, NSM ranges from -44.4 to 42.3 m, with an average of 3.71 m. LRR ranges from -0.75 to 0.66 my^{-1}, with an average value of 0.12 my^{-1}.

In this sector, SCE and the absolute value of NSM are significantly

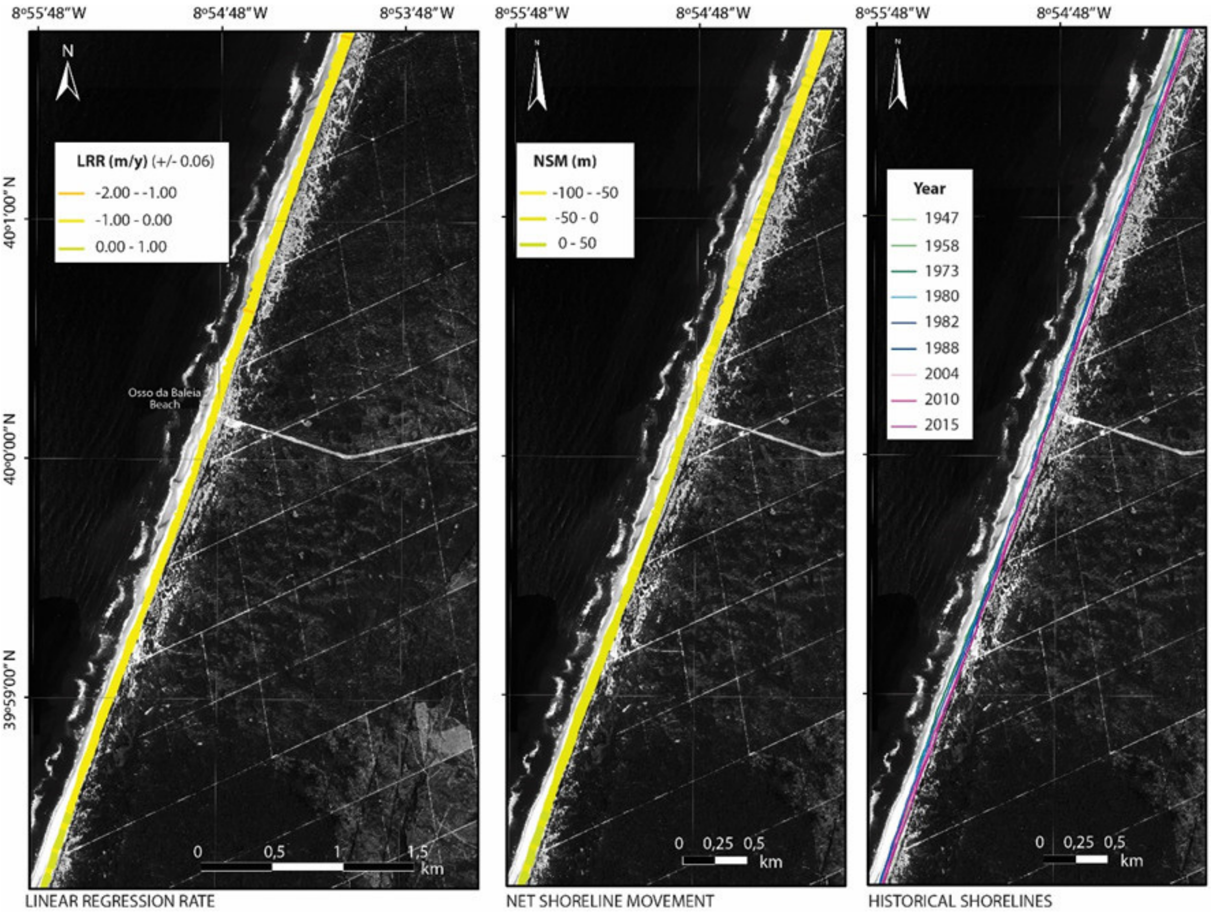

Figure 6. Historical coastline position, Linear Regression Rate (LRR) and Net Shoreline Movement (NSM) for *Osso da Baleia* coastal sector, between 1947 and 2015. Background photo is the 2015 ortophotomap. Map produced using ArcMap, a module from ArcGIS© Desktop 10.6.1 of ArcGIS® software by Esri.

different, with the SCE average being 50.0 m and the Abs(NSM) average 12.3 m, resulting in a CO index, [Abs (NSM)/SCE] of 0.2 (table 2).

4.5 *Praia da Vieira* coastal sector

The erosional tendency observed in the last sector, south of *Pedrogão*, continues in the first part of this sector for approximately 1700 m (figure 8) where it shifts gradually to an accretionary trend that extends southward, for 1710 m, up to the north jetty of *Praia da Vieira*. In this subsector NSM values range from -45.0 to 154.4 m, with an average progradation of 5.6 m. The LRR ranges from -0.54 to 2.51 my^{-1}, with an average rate of accretion of 0.23 my^{-1}.

South of Liz River mouth, which is fixed by two jetties, erosion prevails (figure 8). NSM values range from -84.2 to 12.1 m, with an average erosion of -14.2 m. The LRR ranges from -1.19 to 0.34 my^{-1}, with an average rate of erosion of -0.11 my^{-1}.

Considering the overall 6850 m sector (figure 8), NSM ranges from -84.2 to 154.2 m, with an average of -4.35 m. LRR ranges from -1.19 to 2.51 my^{-1}, with an average value of 0.06 my^{-1}.

The CO index, [Abs (NSM)/SCE], for this sector is 0.5 (table 2) as a consequence of SCE being 1.9 times bigger than NSM.

4.6 *Samouco* coastal sector

The erosional trend detected southwards *Praia da Vieira* continues to the initial part of this sector, with erosion prevailing over the accretion (figure 9) changing, then, gradually towards an accretion tendency, which dominates throughout the south part of the sector. Therefore, in the first 2900 m, where erosion prevails, the average NSM is -11.15 m, while in the last 4260 m, where progradation prevails, the average NSM has a value of 9.87 m.

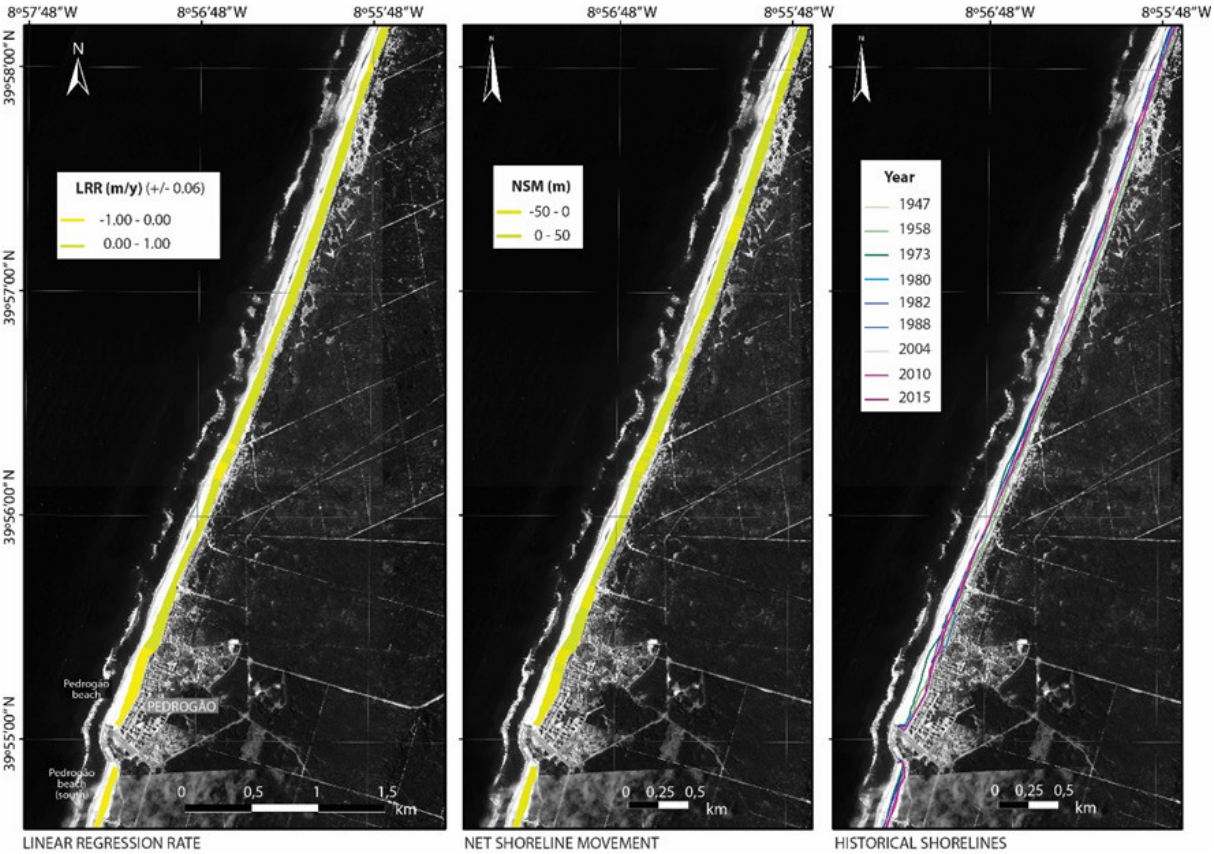

Figure 7. Historical coastline position, Linear Regression Rate (LRR) and Net Shoreline Movement (NSM) for *Osso da Baleia - Pedrogão* coastal sector, between 1947 and 2015. Background photo is the 2015 ortophotomap. Map produced using ArcMap, a module from ArcGIS© Desktop 10.6.1 of ArcGIS® software by Esri.

Considering the entire 7160 m extension (figure 9), NSM ranges from -31.2 to 27.4 m, with an average of 1.36 m. LRR ranges from -0.31 to 0.43 my^{-1}, with an average value of 0.06 my^{-1}.

In this sector, average SCE (21.9 m) is 2.1 times larger (table 2) than the absolute value of NSM (10.4 m).

4.7 *São Pedro de Moel* coastal sector

The *São Pedro de Moel* sector was not fully covered by DSAS analysis, as may be seen in figure 10, because sandy beaches backed by foredunes are not present in some parts of the sector.

Between the end of *Samouco* sector and *São Pedro de Moel*, the 2450 m of coastal stretch shows erosion and accretion, being the later mainly localized in the southern part. The prograding area, with 1790 m in length, has an average NSM of 17.2 m, and the eroding part, with a length of 660 m, has an average NSM of -6.80 m.

Considering the 2450 sector, NSM ranges from -25.4 to 57.2 m, with an average of 10.7 m. LRR ranges from -0.28 to 1.14 my^{-1}, with an average value of 0.29 my^{-1}.

For this sub-sector, the average SCE value, 36.3 m, is significantly larger than the Abs (NSM), which is 14.4 m, leading to an CO index, [Abs (NSM)/SCE], of 0.4 (table 2).

South of *Valeiras*, the 570 m subsector has a NSM maximum of 3.2 m, a minimum of -10.6 m and an average value of 3.72 my^{-1}. LRR ranges from -0.0 to 0.16 my^{-1}, with an average value of 0.08 my^{-1}.

4.8 *Paredes da Vitória* coastal sector

As in the previous sector, the *Paredes da Vitória* coastal sector (figure 11) was not fully covered by our analysis since, although beaches are always present, they are baked up by cliffs and not by dunes, hampering these sectors to fulfil the defined criteria for coastline delimitation.

The analysed parts of the sector, with a total length of 2390 m,

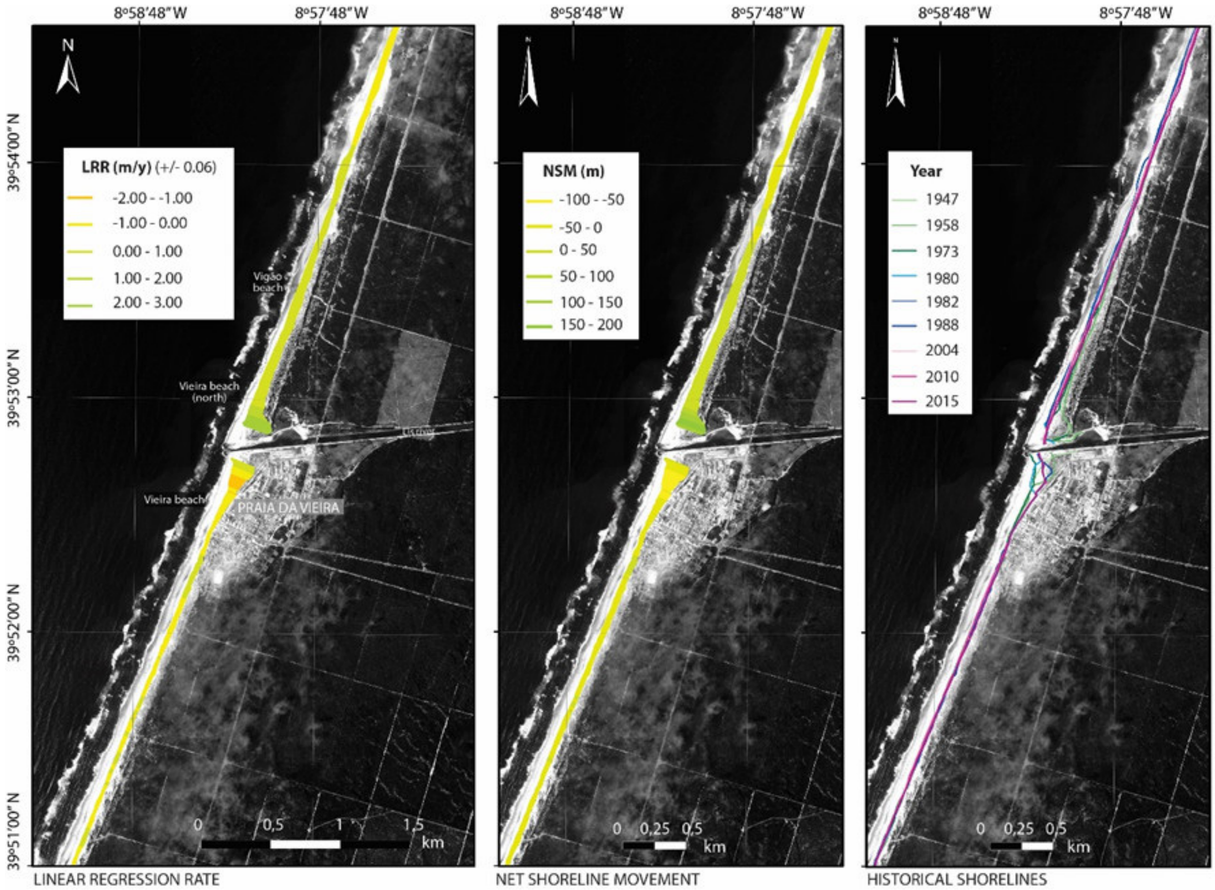

Figure 8. Historical coastline position, Linear Regression Rate (LRR) and Net Shoreline Movement (NSM) for *Praia da Vieira* coastal sector, between 1947 and 2015. Background photo is the 2015 ortophotomap. Map produced using ArcMap, a module from ArcGIS© Desktop 10.6.1 of ArcGIS® software by Esri.

show mainly a stable coastline position with a small accretion tendency, occupying 1990 m of the coastal stretch.

NSM ranges from -9.4 to 36.5 m, with an average of 7.3 m and LRR ranges from -0.06 to 0.61 my^{-1}, with an average value of 0.15 my^{-1}.

4.9 *Vale do Pardo - Nazaré* coastal sector

The *Vale do Pardo – Nazaré* is the last sector of the analysed coastal stretch. With a length of 5560 m (figure 12), it presents an increased accretion trend towards south. NSM ranges from -22.2 to 81.1 m, with an average of 24.62 m, and LRR ranges from -0.10 to 1.67 my^{-1}, with an average value of 0.56 my^{-1}.

Accretion occurs in an extension of 4350 m, with an average NSM of 33.8 m and erosion occurs along 1230 m, with an average NSM of -8.5 m.

5. DISCUSSION

5.1 The importance of coastline evolution trend estimates, at a high-resolution scale

The cartographic assessment of the European coasts exposure to coastal erosion based on spatial data and GIS analysis has been, since the last decades, a mutual international goal as all European coastal states are, to some extent, affected by coastal erosion (Commission, 2004; Ferreira and Matias, 2013). The need of acquired dataset and its analyses, first at a European scale (Ferreira and Matias, 2013), and thereafter at national scale (Lira *et al*., 2016) has been, since then, successfully achieved for the Portuguese scenarios.

However, even though a small-scale dataset is vital for addressing mitigation measures for coastal erosion, the further achievement of updated and reinterpreted regional to local-

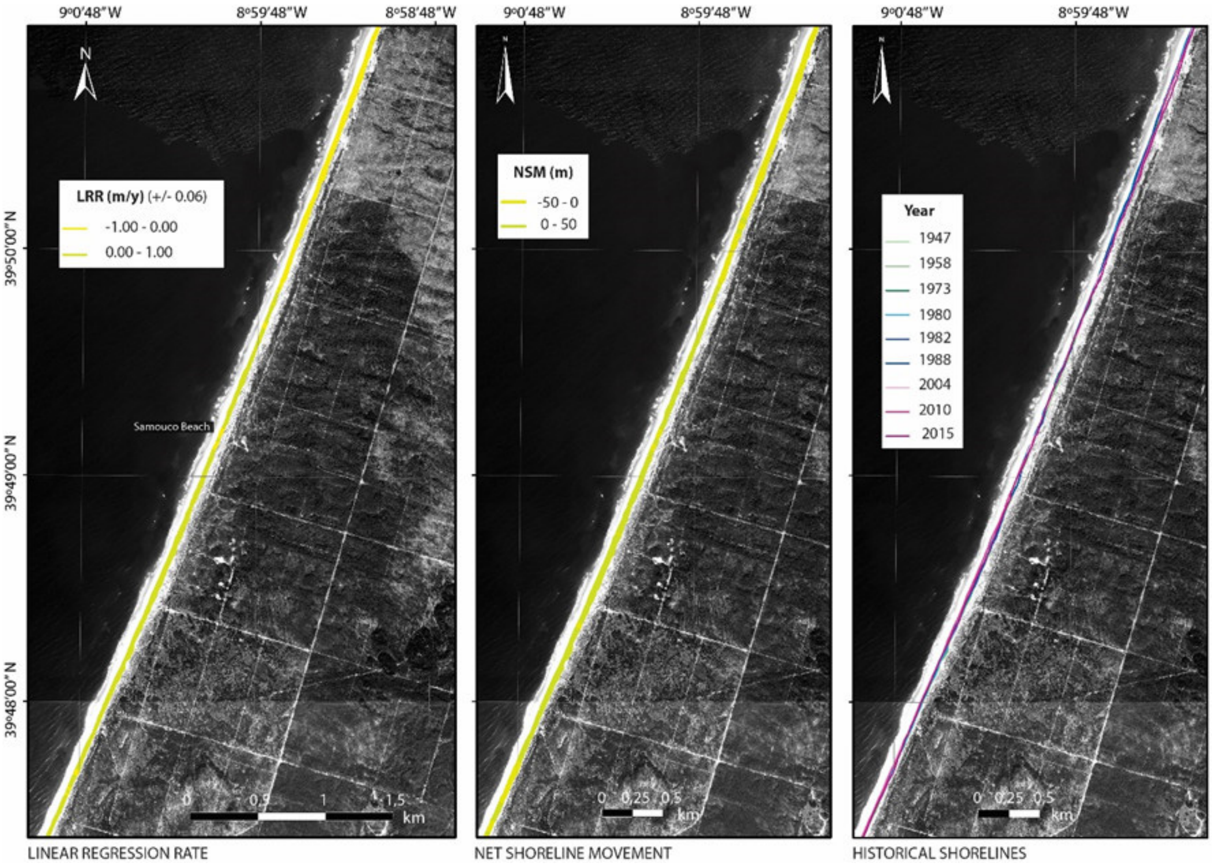

Figure 9. Historical coastline position, Linear Regression Rate (LRR) and Net Shoreline Movement (NSM) for *Samouco* coastal sector, between 1947 and 2015. Background photo is the 2010 ortophotomap. Map produced using ArcMap, a module from ArcGIS© Desktop 10.6.1 of ArcGIS® software by Esri.

scale information, on long-term coastline evolutionary trend, is particularly valuable in areas with strong human occupation and relevant beach erosion, as the mitigation and defence measures to apply in those sectors should be robustly supported and backed by detailed scientific information. This would strongly contribute for the planning and implementation of effective adaptive measures on the climate change scenarios particularly in regions significantly endangered by erosion.

When comparing to previously published results produced at a national scale (Lira *et al*., 2016), the erosion and accretion trends are similar, although the mean coastline rates of change are smaller in the present work and differences are noticed locally with maximum retreat or accretion rates identified in distinct areas.

The differences on local coastal Linear Regression Rates detected at this systematic and high-resolution study, in comparison to the previous national-scale dataset (Lira *et al*., 2016), put in evidence the advantage of the achievement of continuous updated and reinterpreted high-resolution data at a local scale, as a zoomed analysis likely favour to apply the mitigation measures (as sand nourishment and others) at the exact key target locations.

5.2 Coastline evolution trend of the last, nearly, 7 decades at the western sector from *Figueira da Foz* to *Nazaré*

The sedimentary flux, already diminished by the reduced fluvial source at the northward limit of cell 1 (i.e., sub-cell 1a), has long been the central issue that explains the generalized retreat of the western coastal shoreline (Santos *et al*., 2014). The average rate of coastal retreat, NSM, of the last 68 years, calculated in this work (-13.6 m) for the sandy coastline, backed up by dunes, from *Figueira da Foz* and *Nazaré* sector, confirms the previously reported readjustments of the coastal system due to

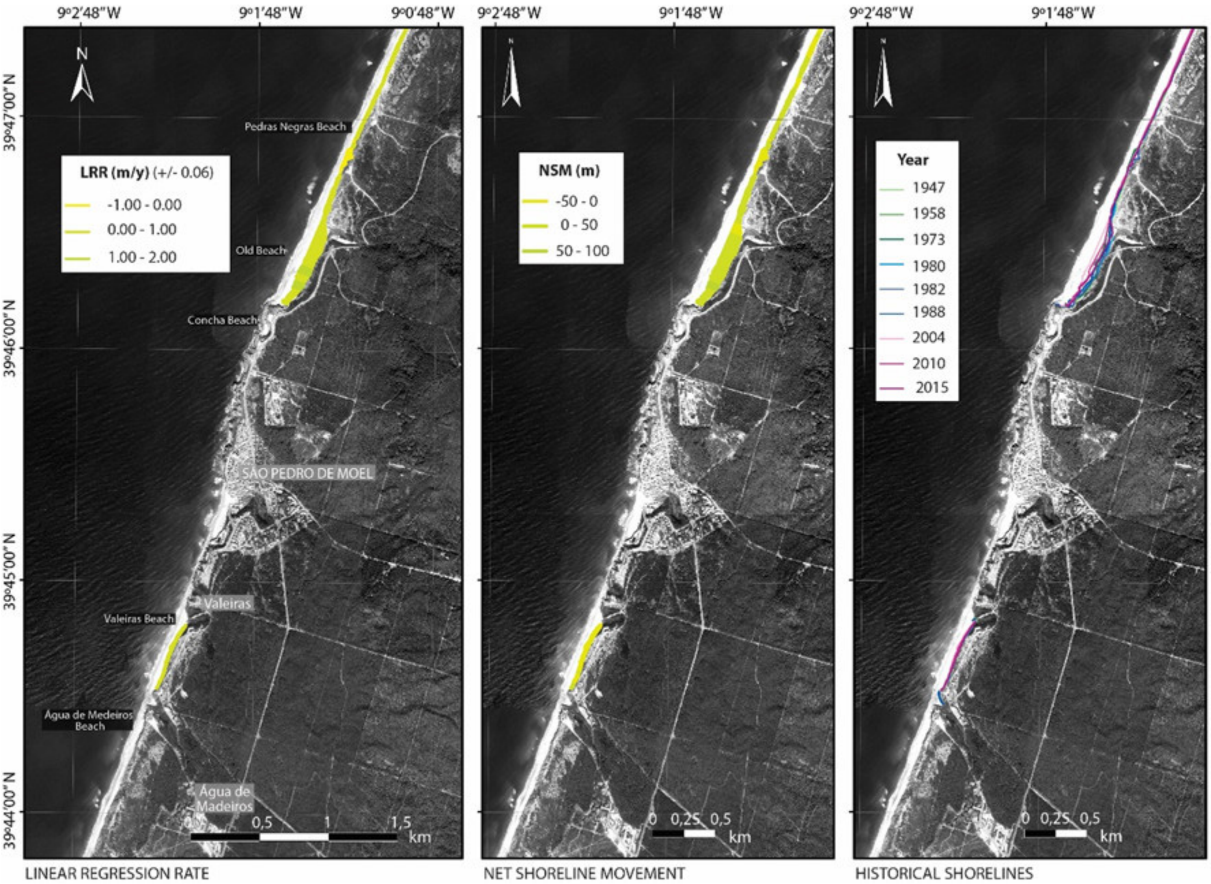

Figure 10. Historical coastline position, Linear Regression Rate (LRR) and Net Shoreline Movement (NSM) for *São Pedro de Moel* coastal sector, between 1947 and 2015. Background photo is the 2010 ortophotomap. Map produced using ArcMap, a module from ArcGIS© Desktop 10.6.1 of ArcGIS® software by Esri.

human occupation and activities, including the introduction of rigid marine structures that hamper and/or retain the sediment transported by the southward course of the coastal drift.

In the present case, the average retreat of the coastline may induce in an error of interpretation since progradation also occurs in a significant extension. Thus, if looking only to the sectors under erosion, which extends for 30 470 m, the average coastline retreat (NSM) is -38.2 m, and the eroded area corresponds to 1 164 888 m^2 (approximately 116 ha). Consequently, the prograding coastline occupies 21 010 m of extension, with an average progradation (NSM) of 22 m, which corresponds to an accretion area of 462 377 m^2 (approximately 46 ha).

It is also important to stress that the NSM data, which in this paper is mostly used to quantify the coastline movement, between the oldest and the most recent coastline position, should be complemented by the SCE to fully understand the coastal behaviour. In the analysed sector, the calculation of the total area associated to the coastline movement resulting from the NSM determination, which is 1 627 265 m^2, is largely exceeded by the area obtained by the SCE value (2 466 377 m^2). Thus, the SCE area, being 52% larger than the NSM area, means that the overall coastline oscillation during the period of analysis was significantly larger than the resultant displacement given by the NSM. This relevant information should be considered when managing local coastal activities, as the SCE index denotes a greater oscillation of the coastline position, in comparison to the NSM index.

5.2.1 Figueira da Foz – Costa de Lavos coastal sector

At the northern limit of this sector there is a small beach anchored between the two southern jetties of *Mondego* River mouth. The evolution of this sector is strongly influenced by the southern jetties of the *Figueira da Foz* inlet. In 1947, a jetty, in the left side of the river, was already in place and downdrift

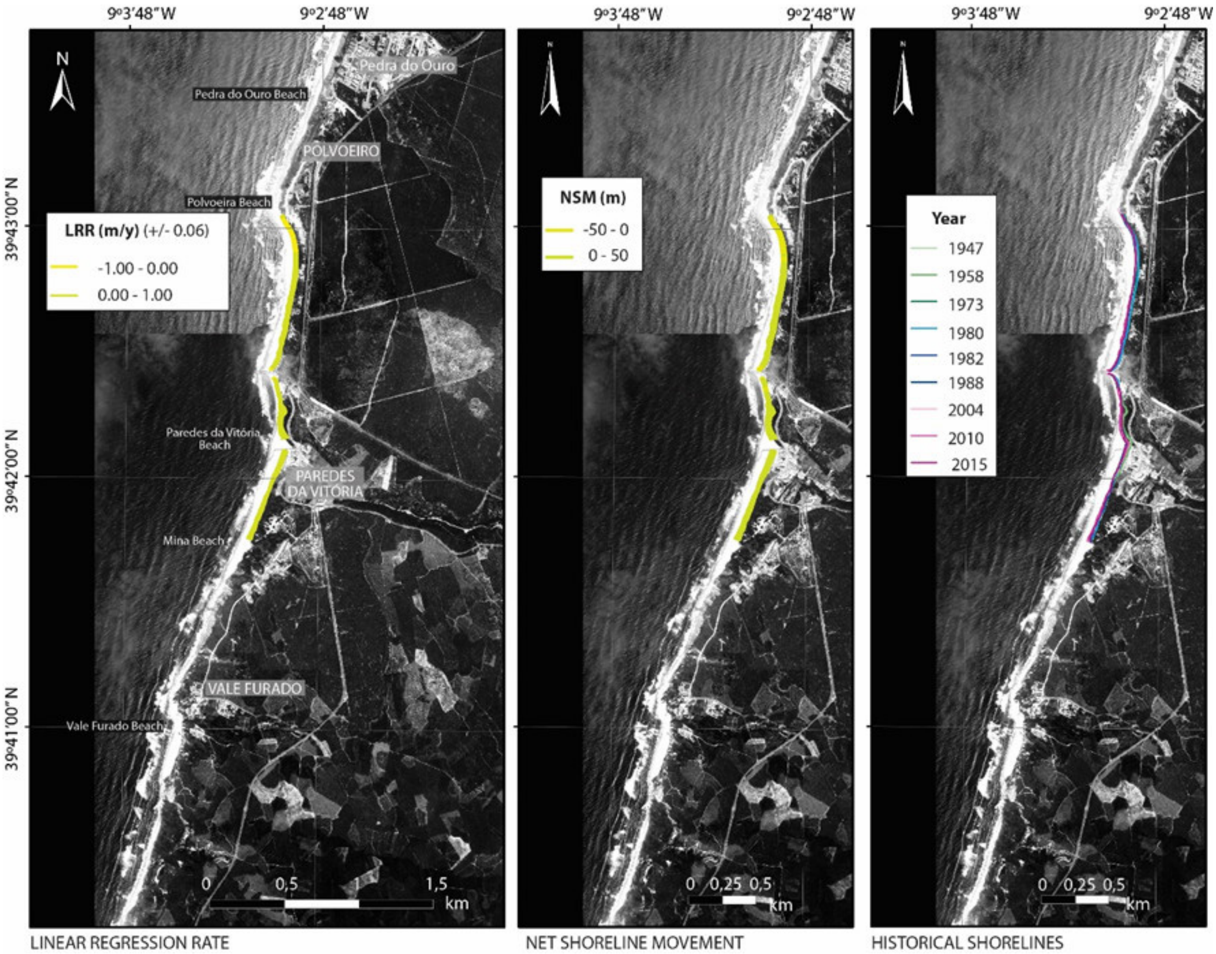

Figure 11. Historical coastline position, Linear Regression Rate (LRR) and Net Shoreline Movement (NSM) for *Paredes da Vitória* coastal sector, between 1947 and 2015. Background photo is the 2015 ortophotomap. Map produced using ArcMap, a module from ArcGIS© Desktop 10.6.1 of ArcGIS® software by Esri.

erosion was already present, being visible by the liner aspect of the foredune/beach contact. In 1958 the erosion was even more evident, with foredune destruction and occurrence of overwash at backdune deposits, northward of *Cova Gala*. Between 1958 and 1973 a new and longer jetty was built approximately 500 m further south and, in the right margin of the river, a new jetty was also built (the jetty responsible for the *Figueira da Foz* beach accumulation). The installation of these two long jetties is the major responsible for the beach accretion.

Between 1982 and 1990 the first groin was expanded, together with the placement of a new one in the right margin, in order to straighten the inlet channel. When analysing the coastlines dataset, the influence of these coastal structures (the internals and the externals) is clear, with the coastlines shifting offshore in accordance with the structure development. Three different sets of coastline positions are visible: the most inshore positions during 1947 and 1958, followed by the intermediate positions during the 70th and 80th decades, and finally, the most offshore positions during 2004 to 2015. During the last 68 years, this beach prograded 198.1 m (NSM) at a 3.3 my^{-1} rate (LRR).

South of this beach, this sector presents a worrisome erosion, along a 5400 m coastal strip, that is only reversed at *Costa de Lavos* area, where a groin, placed between 1973 and 1980, helped to stabilize the coastline position. The reduction of the longshore drift led to a continuous inland coastline shift and to the need to deploy coastal defences in front of *Cova Gala*. The five groins, complemented by seawalls, were built between 1973 and 1980 and manage to reduce the coastline retreat, although the protected coastal stretch continued to be vulnerable to overwash, during storms. The 720 m protected seafront suffered

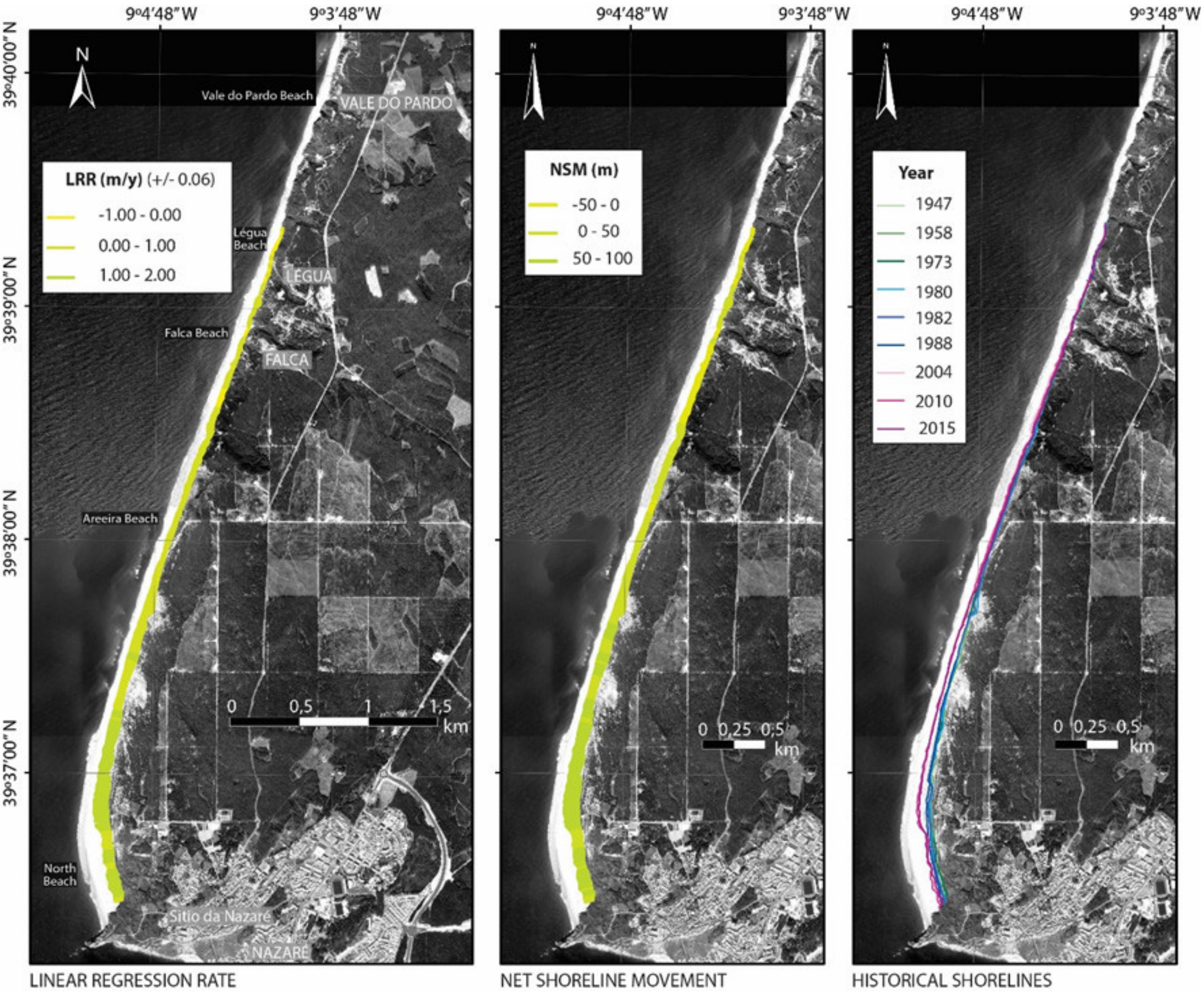

Figure 12. Historical coastline position, Linear Regression Rate (LRR) and Net Shoreline Movement (NSM) for *Vale do Pardo - Nazaré* coastal sector, between 1947 and 2015. Background photo is the 2010 ortophotomap. Map produced using ArcMap, a module from ArcGIS© Desktop 10.6.1 of ArcGIS® software by Esri.

an average coastline retreat (NSM), most of it prior to the defence constructions, of 55 m, with a maximum of 88,6 m, and an average LRR of 0.75 my^{-1}. In contrast, the next 720 m suffered an average coastline retreat (NSM) of 130.5 m, with a maximum of 145.7 m, and an average LRR of 1.89 my^{-1}. Taking in consideration the overall eroding coast, approximately with 5400 m of length, the analysis shows that the average coastline retreat (NSM) is -68 m, with an average rate of erosion (LRR) of 0.92 my^{-1}. The maximum value of retreat, -145.7 m, is located approximately 270 m southward of the last *Cova Gala* groin, and the erosion tends to diminish southwards.

As previously mentioned, a small accretion area is observed at the southern limit of this sector. Along this 500 m end-stretch, a tenuous average accretion (NSM) of 10.6 m, and an average progadation rate of 0.12 my^{-1} is measured. This accretion is related with the *Costa de Lavos* groin, built between 1973 and 1980 with the aim to stop the prevailing erosion.

Human interference induced in coastal dynamics through the introduction of rigid constructions was not able to stop erosion completely and, as a consequence, beach and dune nourishment was carried out. Between 1973 and 1976, 294 020 m^3 of sand were deposited on *Cabedelo* beach (table 3). The reinforcement, with a later nourishment, in 2014, at *Cova Gala* and *Lavos* beach (table 3) had also a negligible effect on 2015 coastline position which is still inland displaced, when comparing to the 2010 position, as it is visible southward *Cova Gala* area.

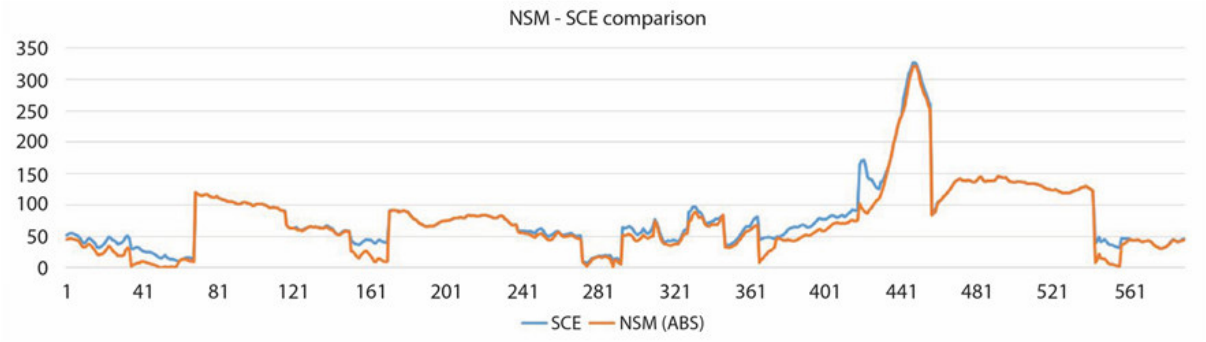

Figure 13. SCE and absolute value of NSM comparison for the *Figueira da Foz* – Costa de *Lavos* coastal sector, showing similarity between both indexes. Vertical axis: Coastal displacement, in meters; Horizontal axis: Coastal sector distance, from the most northern point (in meter x 10).

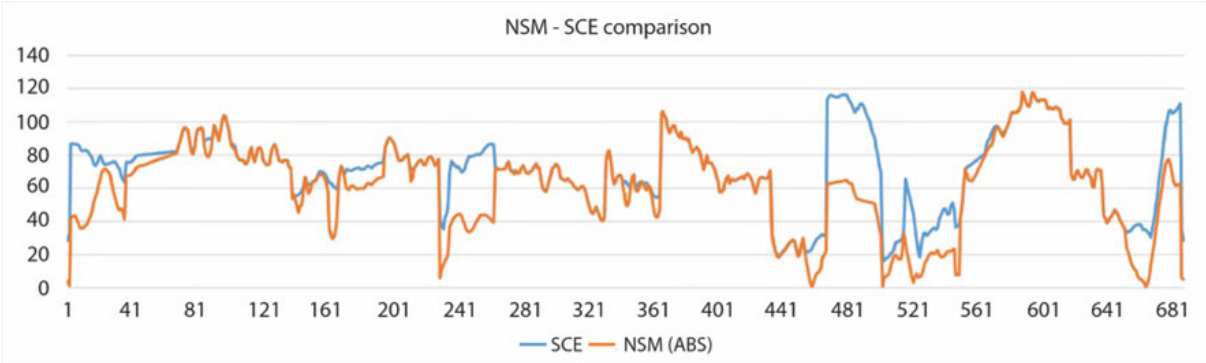

Figure 14. Absolute value of NSM and SCE comparison for the Costa de *Lavos* - *Osso da Baleia* coastal sector, showing similarity between both indexes. Vertical axis: Coastal displacement, in meters; Horizontal axis: Coastal sector distance, from the most northern point (in meter x 10).

Regarding the Coastal Oscillation index, [Abs (NSM)/SCE], (table 2), the value of 0.9 for this sector indicates that NSM gives a good indication of the coastal evolution behaviour during the period of analysis (figure 13), since both lines are almost coincident.

5.2.2 Costa de Lavos – Osso da Baleia (N) coastal sector

This segment (figure 5) is a good example of the effect of perpendicular coastal defences deployment in a longshore drift coastal environment exposed to a negative sedimentary budget. As N-S longshore drift prevails in the study area, groins deployed perpendicular to the coast promote accumulation of sand updrift (in the present case, towards the north of the structures) and erosion downdrift (to the south of the structures).

Therefore, southwards of *Costa de Lavos* groin, erosion is intense (higher value of NSM of -117.8 m, with a LRR of -1.68 my^{-1}), diminishing gradually in the direction of the *Leirosa* groin, where progradation occurs (higher value of NSM of 77.6 m, with a LRR of 0.9 my^{-1}). South of this groin, erosion occurs again (higher value of NSM of -103.7 m, with a LRR of -1.37 my^{-1}) (figure 5).

It is also important to stress that, despite the deployment of coastal defences, erosion continued to occur. To mitigate the erosion effect, an artificial nourishment of sand was done in 2014 at *Leirosa* beach (table 3), but it was not enough to overcome the erosional trend, as the 2015 coastline position is still the one placed at a more inland position (figure 5).

Regarding the CO index, [Abs (NSM)/SCE], (table 2), the value of 0.9 for this sector indicates, like in the previous sector, that NSM is a good indicator of the coastal evolution behaviour during the time period analysed (figure 14).

5.2.3 Osso da Baleia coastal sector

Erosion prevails in the *Osso da Baleia* sector (approximately in 94 % of its length), extending the trend described in the southern part of the preceding sector. Although having an average coastline retreat of -47 m (and an average LRR of -0.51 my^{-1}), no intervention has been made on the coast, since there is no human occupation to protect. Accretion is solely present in the last 400 m of the sector.

The observed erosion is likely the result of the diminishing of the longshore sediment drift (Santos *et al*., 2014). In fact, if we consider a larger area than this sector, from *Leirosa* (in the precedent sector) and Pedrogão (a natural rocky outcrop, in the next sector), the process is similar as it happens between groins: Erosion in the updrift side (north), changing gradually to accretion (which happens in this sector), to a more notorious accretion environment in the southern part, near the natural sand trap obstacle, the *Pedrogão* promontory.

Regarding the CO index, [Abs (NSM)/SCE], (table 2), the 0.8 value indicates, like in the previous sector, that the NSM gives a good indication of the coastal evolution behaviour during the period of analysis. However, a decoupling occurs at the end of this segment (figure 15).

5.2.4 Pedrogão coastal sector

The accretion tendency observed from the southward area of *Osso da Baleia* beach continues to the *Pedrogão* sector (figure 7), being present in 73 % of its length.

From the comparison of SCE and the absolute value of NSM (figure 16), it is noticeable that the two variables differ substantially, being the distance from the oldest (1947) and the most recent (2015) coastline (average of 12.3 m), significantly smaller than the shoreline envelope, SCE (average of 50.0 m). Analysing the coastline positions, an offshore displacement tendency is observed from 1947 until the 70's and 80's, followed by a more recent onshore displacement.

Although the *Pedrogão* promontory, acting like a natural groin, may be seen as responsible for the observed updrift sand accumulation, the coastline instability near that natural structure is significant and erosion is dominant. A road and

Table 3. Beach nourishments, and corresponding characteristics, between 1950 and 2017 for the study area (from Pinto *et al.*, 2018).

Location	County	Date	Volume (m^3)	Deposition type	Loan spot	Device	Objetive
Cabedelo beach (South)	*Figueira da Foz*	1973	50,110	emerged beach	Dredging of the *Coxim* dock	Dredge	Enhancement of the coastline stability conditions
Cabedelo beach (South)	*Figueira da Foz*	1974	69,830	emerged beach	Dredging of the *Coxim* dock	Dredge	Enhancement of the coastline stability conditions
Cabedelo beach (South)	*Figueira da Foz*	1975	88,640	emerged beach	Dredging of the *Coxim* dock	Dredge	Enhancement of the coastline stability conditions
Cabedelo beach (South)	*Figueira da Foz*	1976	85,440	emerged beach	Dredging of the *Coxim* dock	Dredge	Enhancement of the coastline stability conditions
Nazaré harbour beach (southward)	*Nazaré*	2009	28,000	emerged beach	Dredging of the *Nazaré* harbour	Dredge	Enhancement of the coastline stability conditions
Cova Gala beach, *Lavos* beach and *Leirosa* beach	*Figueira da Foz*	2012	100,000	Immersed beach (-2m ZH/-8m ZH)	Maintenance dredging of the *Figueira da Foz* harbour inlet	Dredge	Enhancement of the coastline stability conditions
Cova Gala beach, *Lavos* beach and *Leirosa* beach	*Figueira da Foz*	2013	90,000	Immersed beach (-2m ZH/-8m ZH)	Maintenance dredging of the *Figueira da Foz* harbour inlet	Dredge	Enhancement of the coastline stability conditions
Cova Gala beach, *Lavos* beach and *Leirosa* beach	*Figueira da Foz*	2013	165,630	Immersed beach (-2m ZH/-8m ZH)	Maintenance dredging of the *Figueira da Foz* harbour inlet	Dredge	Enhancement of the coastline stability conditions
Cova Gala beach, *Lavos* beach and *Leirosa* beach	*Figueira da Foz*	2014	110,000	Immersed beach (-2m ZH/-8m ZH)	Maintenance dredging of the *Figueira da Foz* harbour inlet	Dredge	Enhancement of the coastline stability conditions

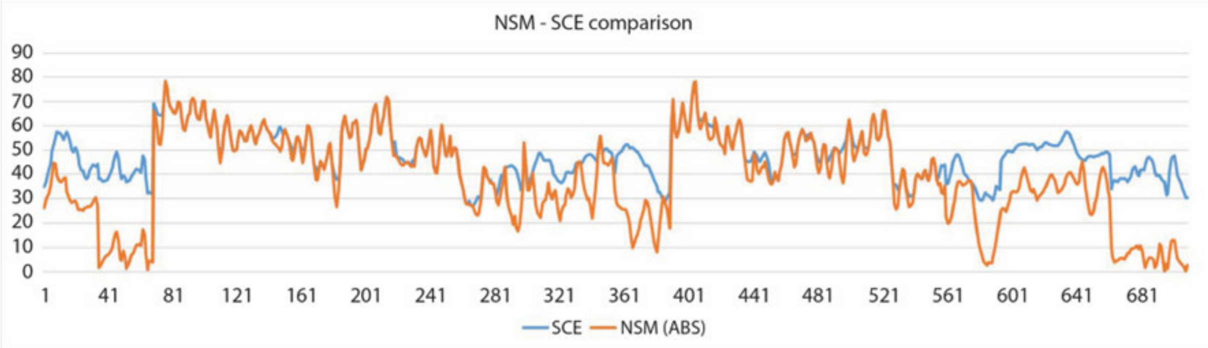

Figure 15. Absolute value of NSM and SCE comparison for the *Osso da Baleia* coastal sector, showing similarity between both indexes, although with a strong decoupling in the beginning and in the ending of the sector. Vertical axis: Coastal displacement, in meters; Horizontal axis: Coastal sector distance, from the most northern point (in meter x 10).

housing were built on top of the foredune and, due to the dune erosion and associated overwash events, a seawall had to be built to protect those structures. Human activity and hard coastal stabilization may have contributed to the unrecovered state of the dune in that particular area.

Southward of *Pedrogão* erosion prevails. This may be interpreted as a result of the littoral drift diminishment during the analysis period.

Regarding the CO index, [Abs (NSM)/SCE] (table 2), the 0.2 value indicates that the NSM has to be used carefully when analysing the coastal evolution behaviour during the analysed time period. SCE is consistently higher than NSM which means that coastline oscillation is significant, playing an important role in this sector (figure 16).

5.2.5 *Praia da Vieira* coastal sector

The most notorious changes in this sector are related with the Liz River mouth, which has been artificially fixed, with two jetties, between 1947 and 1958. These structures induced coastal changes, being that the intensity of the variations diminish with the distance to the inlet.

As previously mentioned, this sector reverts gradually from erosion (related with the *Pedrogão* promontory) to accretion, as we move south in the direction of the Liz River north jetty. The sand accumulation against the jetty starts to be noticeable approximately 1700 m north of the structure. Near the north jetty, accretion reaches 154.2 m in contrast with 26,3 m average of the progradation values observed in the sub-sector, showing the importance of the structure in the longshore drift retention.

Southward of the jetties, as often happens, the erosion reappears, occurring in 3130 of the 3440 m remaining sector length. Immediately south of the second jetty, the erosion reaches -84.2 m in contrast with the sub-sector average, which is -17.1 m, illustrating, once again, the erosional effect of these structures in a longshore drift coastal sand transport.

Erosion values southward of the jetty could be even higher than the ones obtained with the DSAS analysis. *Praia da Vieira* is protected by a seawall and artificial nourishment was already applied to minimize and prevent the coastline inland displacement.

As previously mentioned, the CO index, [Abs (NSM)/SCE], for this sector is 0.5 (table 2). This is a consequence of SCE being 1.9 times higher than the Abs (NSM). However, in the present case, oscillation shouldn't be regarded with great concern once that the CO index values are significantly smaller. Although the ratio is high, the SCE average is only 37.7 m and the average for the absolute value of NSM is 19.8 m, for the last 68 years. Looking to figure 17, it may be concluded that this is a relatively stable coastline, and the oscillation is only more significant in the last 300 m of the sector.

5.2.6 *Samouco* coastal sector

The *Samouco* littoral sector (figure 9), with slight erosion prevailing in the northern part and progradation in the southern part, is the steadiest sector of the study area, with mean LLR of 0.06 $my^{-1.}$

This sector is influenced by two features that lies outside its boundaries: to the north, the *Liz* River jetties and, to the south, the *São Pedro de Moel* promontory. As seen in similar northern sectors, also influenced by hard structures, erosion tends to occur downdrift and sand accumulation tends to occur updrift those structures. This sector, being located between those two hard structures, is in the transition zone, what may explain its stability.

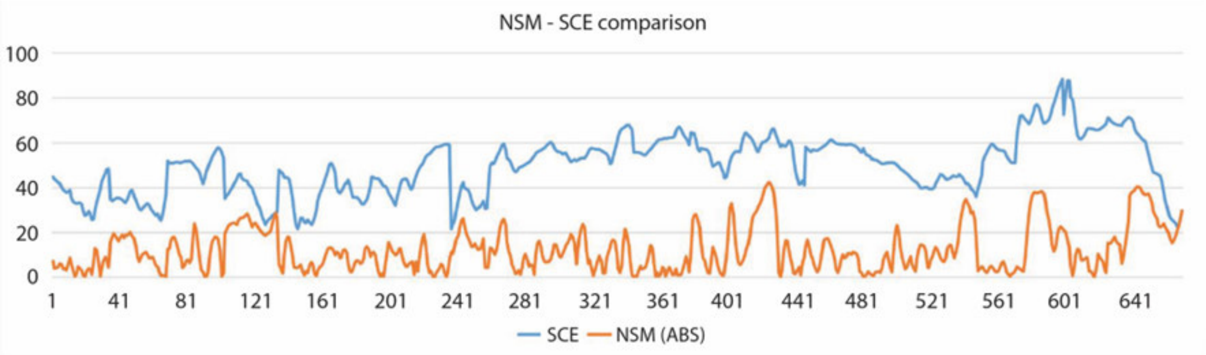

Figure 16. Absolute value of NSM and SCE comparison for the *Pedrogão* coastal sector, showing a strong decoupling from both indexes, with NSM being significantly smaller than SCE. Vertical axis: Coastal displacement, in meters; Horizontal axis: Coastal sector distance, from the most northern point (in meter x 10).

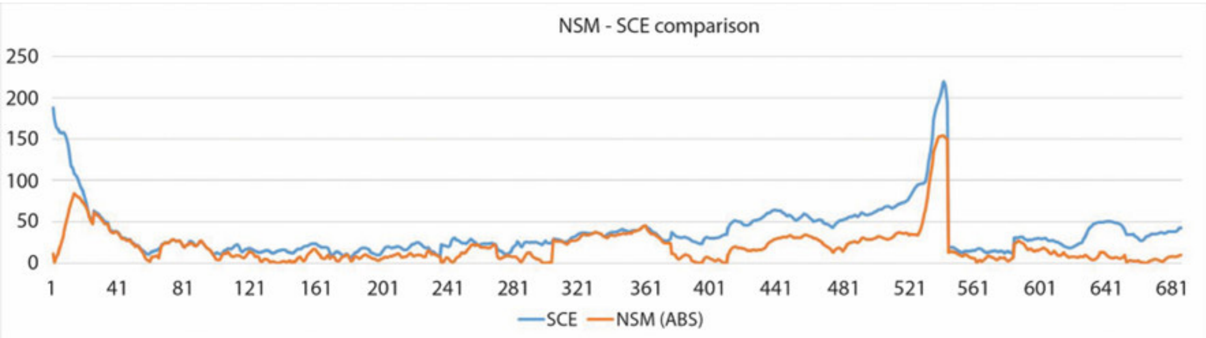

Figure 17. Absolute value of NSM and SCE comparison for the *Praia da Vieira* coastal sector, showing similarity between both indexes, although with a decoupling in the beginning and in the second half of the sector. Vertical axis: Coastal displacement, in meters; Horizontal axis: Coastal sector distance, from the most northern point (in meter x 10).

In this segment, the coastline oscillation follows the same pattern as the one of the southern limit of the predecessor sector, with a slightly decoupling of the SCE and Abs (NSM) indexes (figure 18). With a CO ratio of 2.1, caution should be taken in the analysis of coastline displacement, based solely in the NSM values. However, as coastal changes absolute values are small, with an average NSM of 10.4 m and an average SCE of 21.9 m, the ratio shouldn't be regarded with great concern.

5.2.7 São Pedro de Moel coastal sector

An SCE value approximately 2.5 times larger than the NSM (table 2) is an indication that we are in presence of a coastal stretch where oscillation plays, through time, an important role in the characterization of coastal evolution. The *São Pedro de Moel* rocky shore, already eroded and aligned with the general coastal orientation (figure 10), act as a natural groin, resulting in the updrift accumulation of sand, and establishing a maximum seaward coastline position prior to bypassing occur.

In a finer analysis, the S. Pedro stream also plays an important role in local coastal behaviour. To the north of the stream mouth, nearby *Praia Velha* (located around the 161 (m x 10), in figure 19), the mean SCE value is 19.1 m, while southwards of this beach, the SCE average value is 57.7 m. This higher value is likely related with the observed shift of the mouth stream from 1947 to 2015.

Although the observed coastline oscillation is important in terms of coastal evolution analysis for this sector [Abs (NSM)/ SCE ratio of 0.4, table 2], the LRR value of 0.29 my^{-1}, with shifts between eroding and accretion coastal stretches, indicates that this sector is relatively stable, and the occurred changes may be regarded as part of the natural coastal evolution process in a longshore drift, high energetic coast.

South of *São Pedro de Moel*, the *Valeiras* beach, with 570 m length, has an average NSM value of -3.7 m, showing a slight erosional trend (LRR of 0.08 my^{-1}). However, coastline oscillation has also to be considered, since the average SCE is 16.2 m.

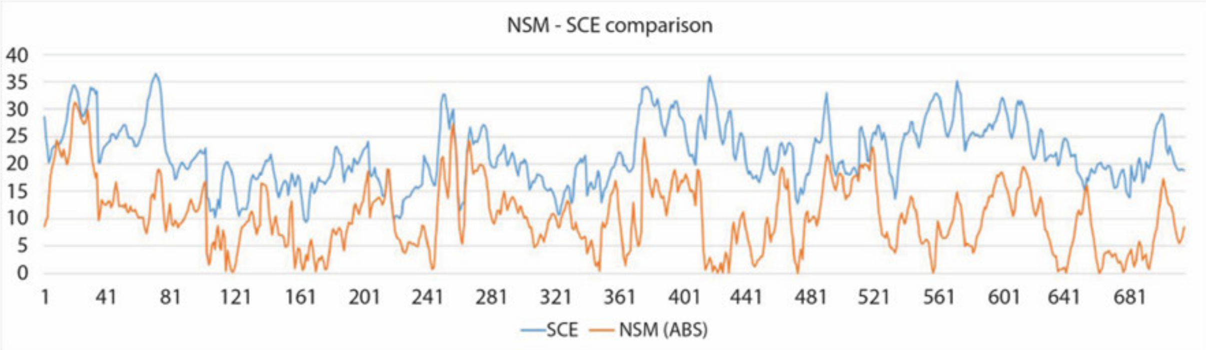

Figure 18. Absolute value of NSM and SCE comparison for the *Samouco* coastal sector, showing some decoupling between both indexes. Vertical axis: Coastal displacement, in meters; Horizontal axis: Coastal sector distance, from the most northern point (in meter x 10).

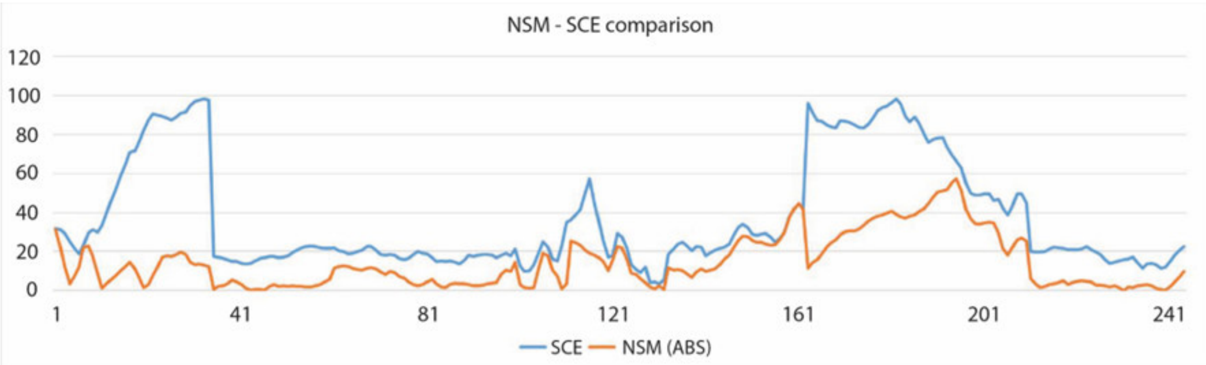

Figure 19. Absolute value of NSM and SCE comparison, north of *São Pedro de Moel*, showing a significant decoupling between both indexes. Vertical axis: Coastal displacement, in meters; Horizontal axis: Coastal sector distance, from the most northern point (in meter x 10).

5.2.8 *Paredes da Vitória* coastal sector

With an SCE value approximately 3 times larger than the NSM, oscillation plays, as in the preceding sector, an important role in the characterization of coastal evolution. Progradation values (NSM average of 7.3 m and LRR average of 0.15 my^{-1}) should, thereby, be valued within this context.

5.2.9 *Vale do Pardo - Nazaré* coastal sector

Although the slightly northward orientation of the coast at these sectors may induce a small increase in the potential of the coastal drift (Santos *et al*., 2014), sand accumulation occurs, confirmed by the presence of wide beaches and well developed dunes (especially in the southern part), where, due to the existence of an aeolian ramp, a sand continuity between the beach/dune system and top-cliff dunes are observed.

Like in the several existent rocky promontories in the coast northward this sector, the *Nazaré* headland has an important role in sand accumulation due to the littoral drift, being the North beach a good example. However, in this sector, the coastline has a peculiar shape (figure 12), drawing a curve and extending seaward, approximately 1 km to the north of the promontory, surpassing what was expected to be the natural coastline orientation. This singular shape of the coastline is due to the effect of the *Nazaré* canyon which tends to rotate the waves orientation anticlockwise (Forone, 2014), promoting a higher accumulation in that area.

This sector, where accretion prevails, may be divided in two subsectors in terms of evolutionary trend. In the first 2470 m of coast, NSM values reflects an oscillation between erosion and accretion. Also in this first subsector, the CO index, [Abs (NSM)/SCE], has a value of 0.3, which reflects a very strong oscillation/instability of the coastal position. In the following 3090 m, accretion is dominant and the Abs (NSM)/SCE ratio has a value of 0.7. However, although ratios are very different, the average difference between the SCE and Abs (NSM) is approximately the

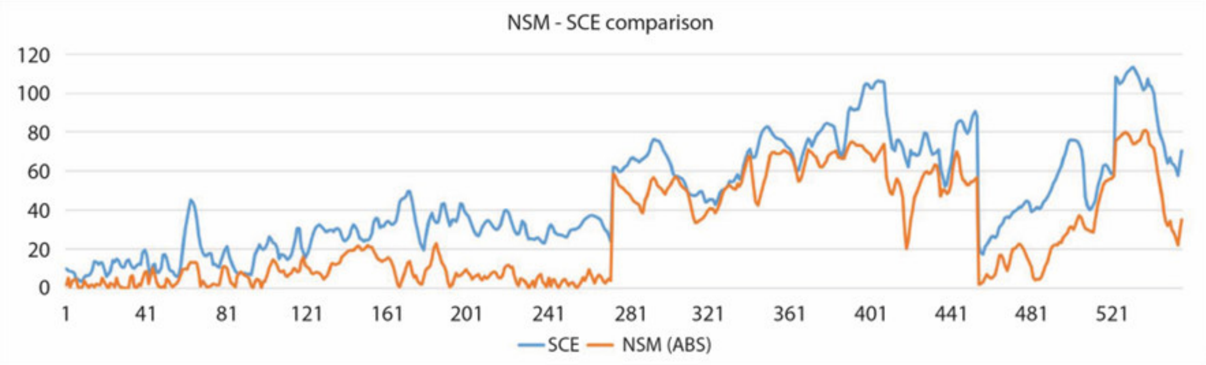

Figure 20. Absolute value of NSM and SCE comparison for the *Vale do Pardo - Nazaré* coastal sector. In the first 2470 meters, coastline oscillation is 3.3 times larger than NSM, whereas in the remaining part of the sector the oscillation is only 1.4 times larger than the NSM. Vertical axis: Coastal displacement, in meters; Horizontal axis: Coastal sector distance, from the most northern point (in meter x 10).

same (16.5 m in the north part and 20 m in the south) (figure 20), showing the precaution that has to be taken when using this ratio alone for coastal displacement analysis: depending on the NSM and SCE absolute values involved, very different ratios may be obtained.

5.3 Land loss by coastal erosion

The obtained data may also be used to quantify the lost and gain of territory due to the coastline shift during the 68-year period of analysis. Considering the positive and negative coastline shifts from 1947 to 2015, data shows that 1 164 888 m^2 of land were lost, along 30 470 m of coast, and 462 330 m^2 were gained, along 21 010 m of coast. The overall result may be expressed as a loss of territory of 702 558 m^2.

Table 4. Land loss and land growth for each sector, based on the NSM values.

Coastal sector	Net Area – land loss/land growth (m^2)
Figueira da Foz-Costa de Lavos	-272097
Costa de Lavos-Osso da Baleia	-347886
Osso da Baleia	-265663
Pedrogão	24632
Praia da Vieira	-29558
Samouco	9722
São Pedro de Moel	24065
Paredes da Vitória	17326
Vale do Pardo-Nazaré	136899
Resultant	**-702558**

The analysis may also be made by sectors, as shown in Table 4. As a result, 4 of the 9 sectors show erosion, while 5 show accretion. Table 4 also displays a clear predominance of erosion in the northern sectors, despite the artificial beach nourishment performed in the northern part, versus a clear tendency for accretion in the southern sectors, during the time-period of analysis.

6. CONCLUSIONS

The current work brings new and detailed insights on the historical evolution trend of the western Portuguese littoral, occupied by beaches with dunes, from *Figueira da Foz* to *Nazaré*. Being part of a broader national programme at LNEG [https://geoportal.lneg.pt/mapa/?escala=4000000&mapa=geologiacosteira#], this study achieves, for the first time, a long-term (nearly 7 decades, from 1947 to 2015), high-resolution (10 m spaced), systematic (with an approximately 10-year analysis interval) and continuous coastline evolution analyses, using different sources of aerial imagery and USGS DSAS software to calculate coastline displacement.

The applied DSAS methodology, widely used and recognized to be appropriated for the current propose, makes the presented dataset easily comparable to other previously acquired datasets, with the advantage of, being a continuous and a high-resolution dataset, becoming more adequate to support the planning and efficacious implementation of adaptive measures, not only in a regional, but also on a local scale. Thus, the current results are valuable, in a scientific perspective, but also, and perhaps most importantly, in an applied context, as the understanding of long-term and mesoscale shore evolution of the Portuguese western coast, is needed for the planning and implementation of effective adaptive measures on the climate change scenarios, in particular in this region, significantly endangered by erosion.

Coastline evolution results for the 68 years' time window, obtained in the coastal stretch comprising beach and dunes (51 480 m of the total 63 408 m coastline extension from *Figueira da Foz* to *Nazaré*), reveals an erosional trend, with an average retreat of -13.6 m, despite the artificial beach nourishments deployed in the area as presented in table 3 (759 650 m3). This erosional trend is also shown by the 702 558 m^2 net land loss area during the analysed period. However, and looking only for the coastal sectors where erosion occurred, a total of 1 164 888 m^2 of land loss was observed.

Erosion, that is more severe in the northern part, reaching a maximum coastal retreat of -145 m and an erosion rate of 2.46 my^{-1} south of *Cova Gala*, is due to a negative sedimentary budget that affects this sector (Santos *et al*., 2014). The erosional pattern seems to be induced by human interference in coastal dynamics, namely by the introduction and enlargement of the original rigid constructions at *Figueira da Foz* harbour and by the *Cova Gala,* Costa de *Lavos* and *Leirosa* groins installation. In these later, the slight updrift accumulation is followed by a much expressive downdrift erosion, the typical pattern of coastal areas subjected to a negative sediment budget littoral drift, with maximum retreats of, respectively, -145, -118 and -103 m.

Seaward displacement of the coastline, occupying approximately 40.8% of the studied area, are mainly present in the southern part, reaching a maximum of 81 m of progradation at *Praia do Norte*, near *Nazaré*, although they are also associated with updrift accumulation against the installed protection groins in the north and central part of the study area (maximum values of 322 m between the *Mondego* jetties, 18 m at *Costa de Lavos*, 78 m at *Leirosa* and 154 m at *Praia da Vieira*).

The importance of coastline evolution trend evaluation, at a high-resolution scale, was somehow evidenced by the current work. The advantage of the achievement of continuous updated and reinterpreted high-resolution data at a regional scale, likely favour successful application of the needed mitigation measures (as sand nourishment, and others) at the exact key target locations.

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Conflicts of interest

The authors declare that they have no conflict of interest

Availability of data and material

Data is available at LNEG GeoPortal:

https://geoportal.lneg.pt/mapa/?escala=4000000&mapa=geologiacosteira#

Authors' contributions

Both authors have been involved with the work, namely in the conception and design of the project, data interpretation and manuscript writing

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