COASTAL EROSION: A NORTHERN-PORTUGUESE CASE STUDY

Ana BIO[1], José Alberto GONÇALVES[1,2], Isabel IGLESIAS[1], José Luís PINHO[3],
Luís VIEIRA[3], José Manuel VIEIRA[3], Gueorgui SMIRNOV[3], Luísa BASTOS[1,2]
[1]Interdisciplinary Centre of Marine and Environmental Research (CIIMAR/CIMAR), University of Porto, Edifício do Terminal de Cruzeiros do Porto de Leixões, Avenida General Norton de Matos, S/N, 4450-208 Matosinhos, Portugal.
[2]Department of Geosciences, Environment and Spatial Plannings, Faculty of Sciences, University of Porto, Rua Campo Alegre 687, 4169 - 007 Porto, Portugal.
[3]Center of Territory, Environment and Construction, Department of Civil Engineering, University of Minho, Braga, Portugal.
**anabio@ciimar.up.pt, jagoncal@fc.up.pt, iiglesias@ciimar.up.pt,
jpinho@civil.uminho.pt, luis.vasquez.vieira@gmail.com,
jvieira@civil.uminho.pt, smirnov@math.uminho.pt, lcbastos@fc.up.pt**

ABSTRACT

Coasts are socio-economically and ecologically highly important, yet vulnerable zones. Increasing pressure from human activities, like tourism, growing settlements and development of infrastructures, as well as climate change impacts, such as predicted sea-level rise and intensification of extreme climate, are likely to increase coastal vulnerability. Coastal Zone Management requires thus an evaluation of coastal dynamics, vulnerability and risks.

The present work studied the morpho-sedimentary dynamics of the Northern-Portuguese Atlantic coast, between Caminha and Espinho. Digital terrain and surface models, derived from LiDAR and aerial photography survey data, collected in 2011, 2017 and 2018, were used to assess beach and dune morphology and to quantify morphodynamics. Coastal dynamics was analysed considering the types of beaches found in the region, being predominantly sandy beaches, sandy beaches with rocky outcrops, pebble and rocky beaches and dominant wind and wave conditions.

On average, and for the whole area studied, the coastline was stable between 2011 and 2017, but retreated more than 17 m between 2017 and 2018. Surprisingly, an increase of 10% was observed for the beach-dune volume between 2011 and 2017. Detailed analysis showed that at least part of the observed increase in volume is due to differences in the methods used to obtain the digital models, and does not represent real sedimentary accretion. Between 2017 and 2018 a decrease of 2% in volume was observed which was in line with the observed coastline retreat. These variations are related to expected seasonal beach dynamics, as surveys were done immediately before and after the winter period. Local dynamics depended furthermore on shore configuration and orientation that determine exposure to wave impacts.

Key words: coastal vulnerability, coastal erosion, coastal risks, morpho-sedimentary dynamics.

RESUMEN

Las áreas costeras son zonas de gran importancia socioeconómica y ecológica, pero a su vez son muy vulnerables. La vulnerabilidad de estas áreas puede aumentar con la creciente presión de las actividades humanas, como el turismo, el crecimiento de las zonas urbanas y el desarrollo de infraestructuras, así como con los impactos del cambio climático, como el aumento previsto del nivel del mar y la intensificación de extremos climáticos. Por lo tanto, es importante evaluar la vulnerabilidad y los riesgos para promover una gestión eficaz e integrada de las zonas costeras.

El presente trabajo estudió los riesgos de erosión para la costa atlántica del norte de Portugal, entre Caminha y Espinho. Para evaluar la morfología de playas y dunas, y para cuantificar los procesos morfodinámicos, se utilizaron modelos digitales de terreno y de superficie, derivados de LiDAR y también datos de campañas de fotografía aérea, para los años 2011, 2017 y 2018. Se analizó la dinámica costera considerando los tipos de playas que se encuentran en la región, siendo predominantemente playas arenosas, playas arenosas con afloramientos rocosos, cantos rodados y playas rocosas, y también las condiciones predominantes de viento y oleaje.

En promedio, y para toda el área estudiada, la línea de costa se mantuvo estable entre 2011 y 2017, pero retrocedió más de 17 m entre 2017 y 2018. Sorprendentemente, se observó un aumento del 10 % en el volumen de la playa/duna entre 2011 y 2017. Un análisis más detallado mostró que parte del aumento de volumen observado se debe a diferencias en el método utilizado para obtener los modelos digitales, no representando una acumulación sedimentaria real. Entre 2017 y 2018 se observó una disminución del 2 % en volumen, de acuerdo con el retroceso observado en la línea de costa. Estas variaciones en las playas están relacionadas con la dinámica estacional esperada, ya que las campañas se realizaron inmediatamente antes y después del período invernal. La dinámica local también presenta una dependencia con la configuración y la orientación de la costa, la cual determina la exposición a los impactos de las olas.

Palabras clave: vulnerabilidad costera, erosión costera, riesgos costeros, morfodinámica.

1. INTRODUCTION

Coasts are dynamic land-ocean interfaces that provide numerous ecosystem services, including the service of coastal buffering and protection. This is particularly important considering that about 40% of the world's population live within 100 km of the coast. In Portugal, with its vast coastline and archipelagos, more than 90% of the population live within 100 km of the coast, and about 60% within 25 km.

However, more than 20% of the European and 30% of the Portuguese coastline are estimated to suffer from coastal erosion (Commission et al., 2004), exposing coastal ecosystems and infrastructures to wave impacts and floods, and causing land and property losses (Pollard et al., 2019). This has led to protection and mitigation measures, both through the implementation of hard defence structures, and, increasingly, through soft measures like beach nourishment and other nature-based solutions aimed at protecting beaches and dunes and capturing sediments (Turner et al., 2007; Marinho et al., 2019; Lima et al., 2020). About 14% of the Portuguese coast is currently defended by artificial structures (APA et al., 2017), but, given their frequent unwanted effects, artificial beach nourishment, placement of fences, construction of footbridges and revegetation of dunes are gaining in popularity (Marinho et al., 2019). Coastal dynamics is thus an important issue in coastal management, particularly in the light of climate change and its predicted effects, which may exacerbate erosional trends, through sea level rise and changes in climate patterns.

Coastal morphology is shaped by natural phenomena, such as ocean waves and coastal currents, wind and river-flow effects, as well as by human interventions and activities, like urbanizations and infrastructures, and man-made defence structures (Guillén et al. 1999; Van Rijn, 2011). Sedimentary dynamics will furthermore depend on geological features, and the setting and exposure of the coast line.

In the present work, the morphology and morpho-sedimentary dynamics of the northern-Portuguese Atlantic coast between Espinho and Caminha was studied. Digital terrain and surface models, derived from LiDAR and aerial photography survey data, collected in 2011, 2017 and 2018, were used to obtain morphometric and morphodynamic vulnerability indicators, and assess beach and dune sedimentary dynamics. Dynamics was analysed considering beach sedimentary characteristics and exposure.

2. METHODS

2.1. Study area

The study area comprises a coastal stretch of about 80 km length in northern Portugal (Fig. 1), between the cities of Caminha in the north and Vila Nova de Gaia in the south. This coast is exposed to the highly energetic Atlantic Ocean, with mean significant wave heights between 2 m and 3 m, and mean wave periods between 8 s and 12 s (Viitak et al., 2021). Wave incidence is predominantly from NW, causing a N-S longshore drift, which is locally altered by hard defence structures (groynes and breakwaters) that affect hydrodynamics through wave refraction. The coast displays numerous urbanized stretches and sandy, rocky and pebble beaches.

2.2. Surveys and digital terrain/elevation models

Data from three surveys were analysed: a Digital Terrain Model (DTM) from an airborne LiDAR survey from November/December 2011 and two Digital Elevation Models (DEM) obtained from airborne photography surveys carried out in November 2017 and May 2018.

The DTM from the LiDAR survey (supplied by the DGT – Direção-Geral do Território, www.dgterritorio.gov.pt) covers the coast up to 600 m inland, with a spatial resolution of 1 m. Validation of these elevation data showed a mean squared error of 15.4 cm, with an error less than 26 cm for 90% of the tested control points.

The 2017 and 2018 DEM were derived from surveys carried out in the scope of the MarRisk project (0262_MarRISK_1_E). In each survey, a series of photographs (with an overlap of 80%) was obtained, along a single track, using a photogrammetric camera (Vexcel UltraCam Falcon, 9420×14430 pixels) mounted on a small manned airplane. Flight height was about 1900 m, resulting in a ground sampling distance of approximately 15 cm. Photographs were processed using Agisoft Photoscan software (Agisoft, 2022), to generate a DEM and an orthomosaic with precise georeferencing derived from ground control points. The DEM were generated with a spatial resolution of 50 cm and had a final accuracy in the order of 10 cm (Gonçalves et al., 2011, 2018). Beaches were classified based on in-situ observations, distinguishing: Type 1 – rocky shores; Type 2 – sandy beaches with rocky outcrops; Type 3 – pebble beaches with rocky outcrops; and Type 4 – predominantly sandy beaches.

2.3. Wave and wind conditions

Average significant heights (Hs) and wave peak directions for 3 h intervals were obtained from an offshore directional wave buoy (location: 41°19.00’ N, 008°59.00’ W; data supplied by the Portuguese Hydrographical Institute—IH).
Wind velocity and direction were obtained from the ERA5-Land reanalysis dataset (Muñoz Sabater, 2019).

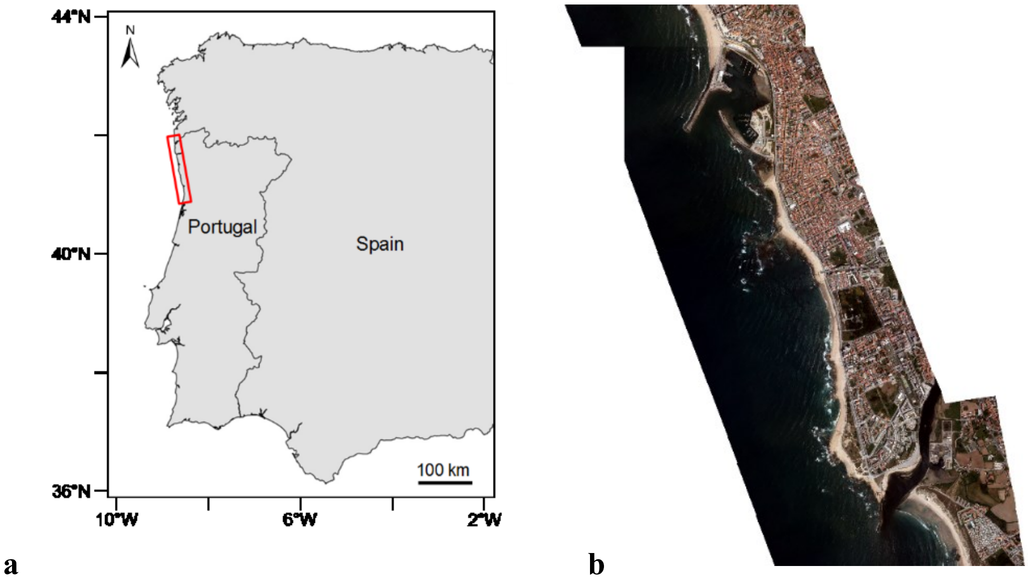

Fig. 1: Location of the study area in northern Portugal (a) and part of the orthomosaic of the May 2018 survey, showing the stretch between the port of Póvoa de Varzim, in the north, and the mouth of the river Ave in the south (b).

2.3. Analyses

The DTM and DEM, were mapped and analysed in a GIS tool (using ArcGIS 10.6 and its Spatial Analyst and 3D Analyst modules). Only the beach-dune system was considered, i.e. urbanized and agricultural areas were excluded from the analyses. To allow an analysis per beach type, the coastal stretch was segmented, considering the limits of parishes and beach types. Average beach width, volume and area were calculated for the whole stretch and for the different segments. Sediment budgets and changes in shoreline position were computed for the periods between surveys.

Shoreline was determined using the 1.05 m isoline above the mean sea level (Cascais 1938 MSL) as a proxy. For the DEM, this line had to be simplified (Fig. 2). To obtain comparable results, the morphodynamics was evaluated per linear meter of coast.

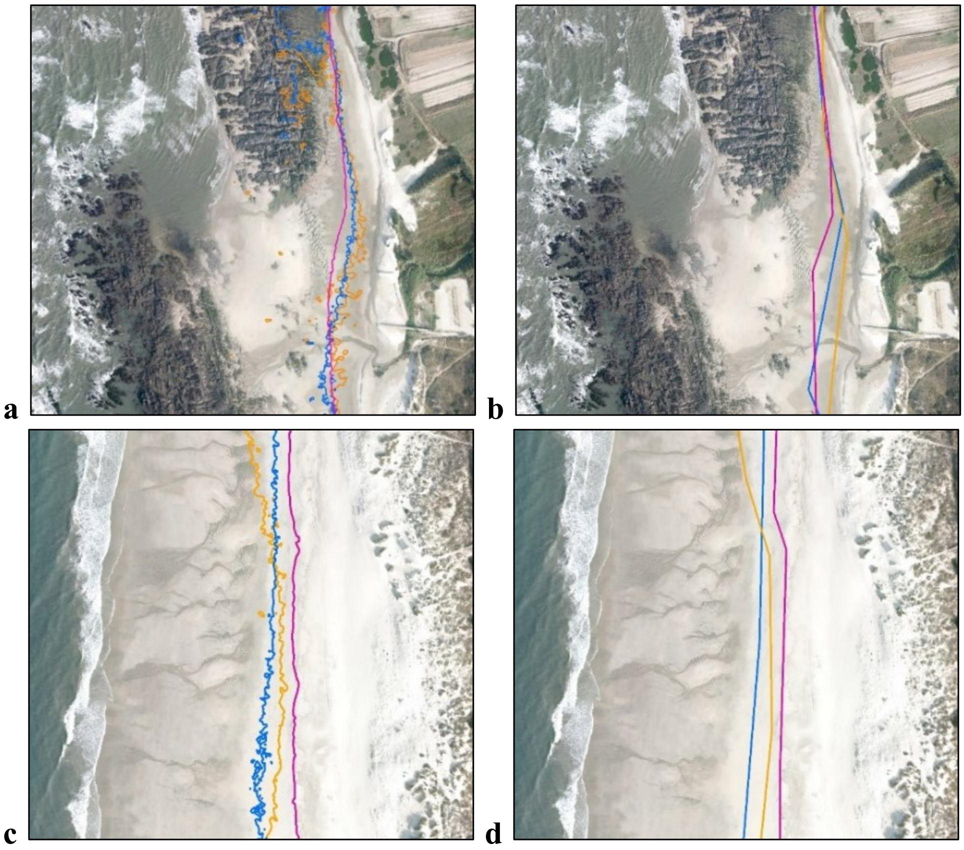

Fig. 2: Shoreline positions at two different beaches: the 1.05 m isolines of the 2011 DTM (pink), 2017 DEM (blue) and 2018 DEM (orange) (a, c) and the simplified shoreline used for the analyses (b, d).

3. RESULTS

Overall, and according to the digital models, the beach-dune system volume increased by about 7.7% between 2011 and 2018 survey. However, the two analysed time periods – 2011/2017 and 2017/2018 – showed contrasting behaviours. The total volume of the beach-dune system increased by 10.0% between 2011 and 2017, but decreased by 2 percent between 2017 and 2018. The shoreline position was relatively stable between 2011 and 2017, but retreated on average 1.5 m between 2017 and 2018. Segmentation of the study area resulted in 87 segments, varying between 18 m and 5332 m in length and between 5 and 407 m in width. Most segments were characterized as sandy beaches with rocky outcrops, followed by predominantly sandy and by rocky beaches; only 3 segments were of the pebble beach type (Tables 1 and 2).

Segment type	**Count**	**between 2011 and 2017**			**between 2017 and 2018**		
		accret	**erosion**	**Δ volume (m^3/m)**	**accret**	**erosion**	**Δ volume (m^3/m)**
All	87	80%	20%	71.20	38%	62%	–17.14
rocky	21	95%	5%	93.65	40%	60%	–6.12
sandy with rocky outcrops	41	78%	22%	55.73	44%	56%	–9.56
pebble with rocky outcrops	3	67%	33%	22.20	67%	33%	–1.54
predominantly sandy	22	73%	27%	100.90	23%	77%	–43.13

Table 1: Changes in beach-dune system volume between surveys, for the different beach types: percentage of segments of a given type showing accretion (accret.) or erosion, and average change in volume per linear meter of coastline.

Segment type	**Count**	**between 2011 and 2017**			**between 2017 and 2018**		
		prog.	**regr.**	**movemen t(m)**	**prog.**	**regr.**	**movement (m)**
All	87	59%	41%	0.02	38%	62%	–1.53
rocky	21	62%	38%	–0.77	43%	57%	–0.27
sandy with rocky outcrops	41	63%	37%	0.04	44%	56%	–0.73
pebble with rocky outcrops	3	67%	33%	–0.22	33%	67%	–1.61
predominantly sandy	22	45%	55%	0.50	23%	77%	–3.94

Table 2: Changes in shoreline position between surveys, for the different beach types: percentage of segments of a given type showing progradation (prog.; seaward movement) or regression (regr.; landward movement), and average shoreline movement.

Between 2011 and 2017, 80% of the segments increased in volume, with an average sediment budget of 71.2 m^3 per linear meter of coast. Between 2017 and 2018, on the other hand, volume decreased in 62% of the segments, with an average sediment loss of 17.1 m^3 per linear meter (Table 1). The dynamics of the shoreline position followed that trend, with 59% of the segments showing shoreline progradation (seaward movement) between 2011 and 2017, though shoreline position on average was stable, yet 62% showing regression (landward movement) between 2017 and 2018, with an average regression of 1.5 m (Table 2). Segment volume and shoreline dynamics varied per beach type, but, apparently, in an inconsistent way. For instance, rocky beaches, expected to be the least dynamic, were the most stable beach type between 2017 and 2018, but comparatively dynamic between 2011 and 2017. For the second period, which corresponds to a winter and early spring, erosion and shoreline regression were most accentuated in predominantly sandy beaches, as could be expected.

Local morphodynamics is also shaped by meteo-ocean conditions, which showed dominant wave directions from NW to WNW and strong winds coming mostly from NNW, especially in the summer, with a SSW component, mostly occurring in winter, by the littoral drift from N to S, and by structures, like groynes. Patterns differed per period, showing, for instance, next to a groyne, the expected downdrift erosion and updrift accretion between 2011 and 2017, but the inverse pattern for the winter period between 2017 and 2018; the second period being characterized by more western waves and more southern winds (Fig. 3).

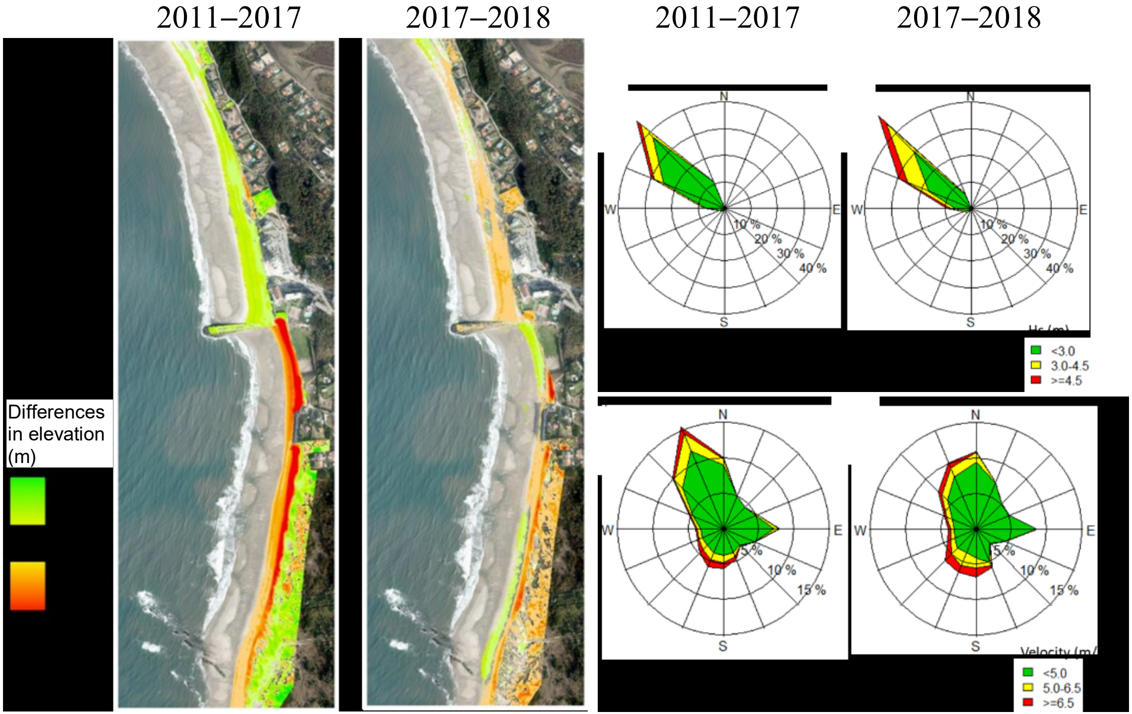

Fig. 3: Erosion/accretion patterns next to a groyne and wave (top) and wind (bottom) roses, for the periods between the 2011 and 2017 and between the 2017 and 2018 surveys.

An in-depth analysis revealed that part of the observed dynamics, particularly in terms changes in volume, was not due to sediment erosion or accretion. Two confounding issues were identified: dune vegetation and methodological aspects. Some dunes have vegetated areas, with shrubs or trees. Firstly, the DEM map the elevation of the terrain and of everything on top of it. The growth of vegetation will therefore result in an increase of volume, i.e. an apparent accretion. Secondly, analyses compare a DTM and two DEM. The DTM was obtained through radar, which penetrates vegetation, with images being filtered to represent the earth surface. The DEM were obtained through photogrammetry, which does not distinguish sand or rocks from vegetation.

Hence, DEM will show higher volumes than DTM in vegetated areas (Fig. 4). Furthermore, we found that the processing of the DTM caused some errors, eliminating parts of the rocky outcrops and thus a part of the beach volume (Fig. 5).

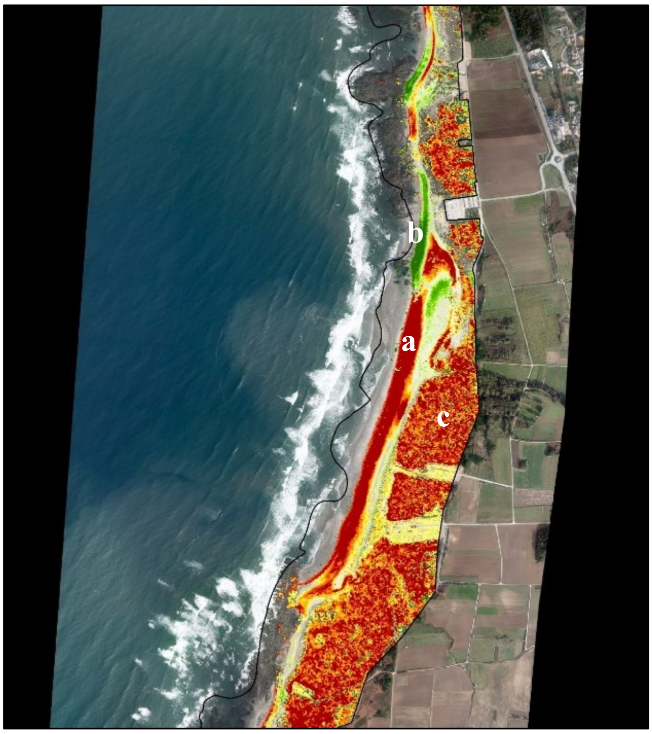

Fig. 4: Differences in elevation between the 2017 and 2018 DEM, with areas showing loss (red) and gain in volume (green) due to sedimentary dynamics at the shore (a, b), and mostly loss in volume in the dunes (c) which is due to changes in vegetation cover/height.

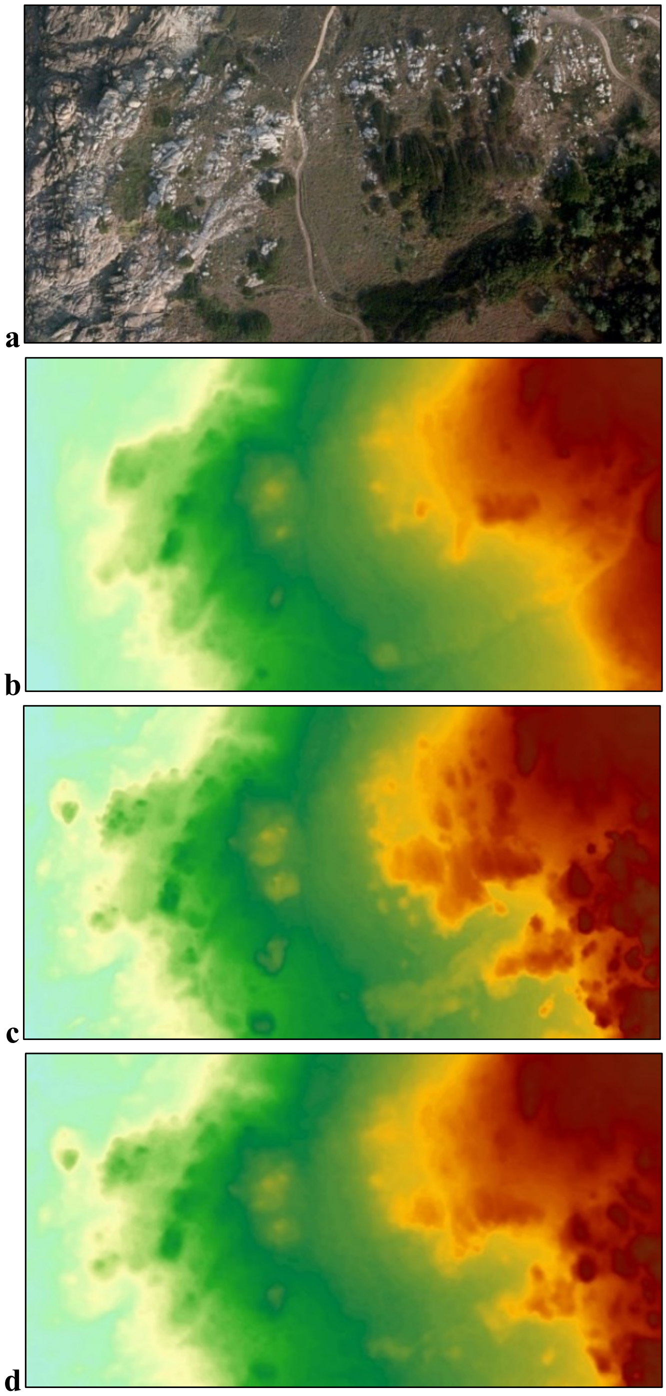

Fig. 5: Orthomosaic (a), 2011 DTM (b), 2017 DEM (c) and 2018 DEM (d) for an area with rocky outcrops; notice how the DTM is smoothed in comparison to the DEM and how rock peaks are smoothed out.

4. DISCUSSION

Comparison of the digital terrain and elevation models suggests that the studied coastal stretch showed overall accretion, yet shoreline retreat, between 2011 and 2018, with a period of increasing volume and stable shoreline position (2011-2017) followed by a period of erosion and shoreline regression (2017-2018). The first (6-year) period represents short to medium-term changes, whereas the second (5-months) period is likely to represent seasonal behaviour. Hence, winter conditions marked by more severe weather and wave conditions, may have contributed to the observed erosion and shoreline retreat observed between 2017 and 2018, which may be compensated by recovery during the following months.

In-depth image and DTM/DEM analysis revealed that the calculated variations in volume were partly due to characteristics of the models themselves. A DTM represents the earth surface, a DEM the observed surface, including vegetation. This explains at least part of the marked increase in volume obtained for the comparison between the 2011 DTM and the 2017 DEM. Furthermore, the DEM was found to show excessive smoothing in rocky areas. This will have contributed to a lower volume in the 2011 data and, furthermore, explain why rocky shores showed such unexpected dynamics between 2011 and 2017. Comparisons between DTM and DEM should therefore be handled with care.

ACKNOWLEDMENTS

This research was partially supported by the Strategic Funding UIDB/04423/2020 and UIDP/04423/2020 through national funds provided by FCT—Foundation for Science and Technology and European Regional Development Fund (ERDF). This work was further funded by the European Union MarRISK project: Adaptación costera ante el Cambio Climático: conocer los riesgos y aumentar la resiliencia (0262_MarRISK_1_E), through EP INTERREG V A España-Portugal (POCTEP) program, and by the project EsCo-Ensembles (PTDC/ECI-EGC/30877/2017), co-financed by NORTE 2020, Portugal 2020 and the European Union through the ERDF, and by FCT through national funds.

REFERENCES

Agisoft LLC. (2021). Agisoft Metashape User Manual Professional Edition, Version 1.7. *Agisoft Metashape*, *September*.

Commission, E., & Others. (2004). Living with Coastal Erosion in Europe--Sediment and Space for Sustainability. In *Luxembourg: Office for Official Publications of the European Communities*.

Gonçalves, J., Bastos, L., Pinho, J., Granja, H. (2011). Digital aerial photography to monitor changes in coastal areas based on direct georeferencing. 5th EARSeL Workshop on Remote Sensing of the Coastal Zone, Prague, June 2011. Available at: http://www.conferences.earsel.org/abstract/show/2689.

Gonçalves, J.A., Bastos, L., Madeira, S., Magalhães, A., Bio, A. (2018). Three-dimensional data collection for coastal management–efficiency and applicability of terrestrial and airborne methods. *International Journal of Remote Sensing*, 39(24), 9380-9399. doi: 10.1080/01431161.2018.1523591

Guillén, J., Stive, M. J. F., & Capobianco, M. (1999). Shoreline evolution of the Holland coast on a decadal scale. *Earth Surface Processes and Landforms*, *24*(6).

https://doi.org/10.1002/(SICI)1096-9837(199906)24:6<517::AID-SP974>3.0.CO;2-A

Lima, M., Coelho, C., Veloso-Gomes, F., & Roebeling, P. (2020). An integrated physical and cost-benefit approach to assess groins as a coastal erosion mitigation strategy. *Coastal Engineering*, *156*(November 2019), 103614. https://doi.org/10.1016/j.coastaleng.2019.103614

Marinho, B., Coelho, C., Hanson, H., & Tussupova, K. (2019). Coastal management in Portugal: Practices for reflection and learning. *Ocean and Coastal Management*, *181*(July), 104874. https://doi.org/10.1016/j.ocecoaman.2019.104874

Muñoz Sabater, J. (2019) ERA5-Land Hourly Data from 1981 to Present. Climate Data Store. https://doi.org/10.24381/cds.68d2bb30.

Pollard, J. A., Spencer, T., & Brooks, S. M. (2019). The interactive relationship between coastal erosion and flood risk. *Progress in Physical Geography*, *43*(4), 574–585. https://doi.org/10.1177/0309133318794498

Van Rijn, L. C. (2011). Coastal erosion and control. *Ocean and Coastal Management*, *54*(12). https://doi.org/10.1016/j.ocecoaman.2011.05.004

Viitak, M., Avilez-Valente, P., Bio, A., Bastos, L., Iglesias, I. (2021). Evaluating wind datasets for wave hindcasting in the NW Iberian Peninsula coast. *Journal of Operational Oceanography*, *14*(2), 152-165. https://doi.org/10.1080/1755876X.2020.1738121