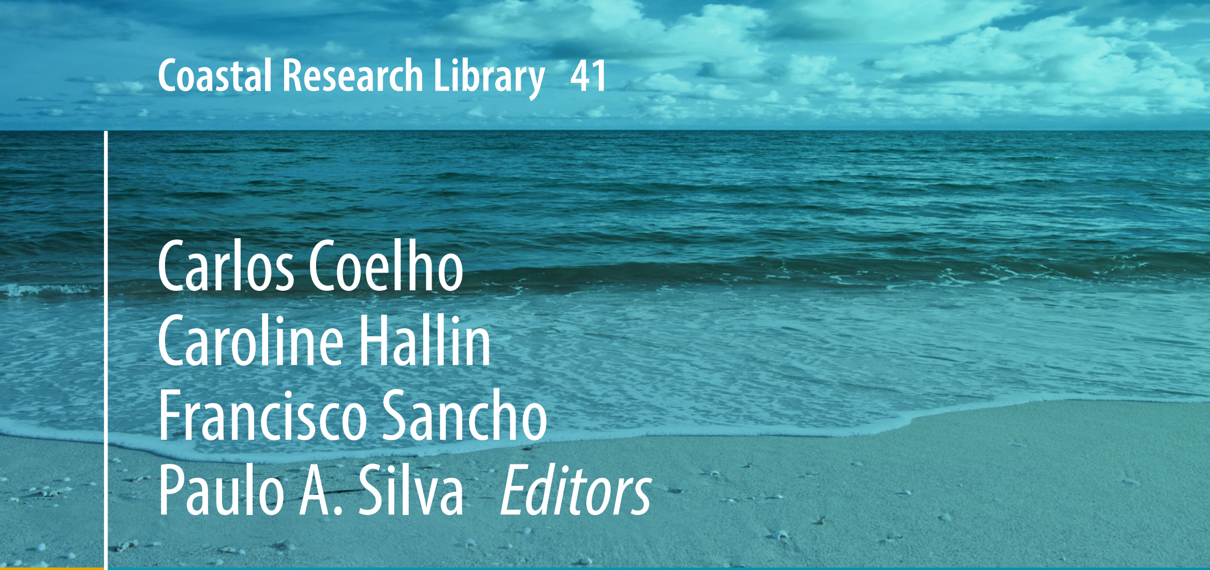

Coastal Research Library 41

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Coastal Dynamics 2025

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Decoding Storm Response in Geologically Controlled Coastal Barriers Using XBeach

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Abstract. Storm-induced morphological changes in coastal barriers are primarily driven by hydrodynamic forcing. However, in rock-fronted coasts the presence of geological features can modulate storm impacts, but the extent to which these non-dynamic variables influence barrier morphological response to storms is still poorly understood. This study explores the influence of intertidal rock platforms on storm-driven morphological changes. Using the process-based XBeach model, dune erosion during an energetic winter storm was simulated across different schematic cross-shore profiles, incorporating variable intertidal rock platform configurations. The schematic profiles are based on existing barrier profiles in the Outer Hebrides, NW Scotland. Calibration of the model involved adjusting friction coefficients of exposed bedrock surfaces to improve the ability to reproduce observed nearshore wave heights and morphological changes in pre- and post-storm profiles. The results show that higher intertidal rock platforms (above mean sea level) are associated with reduced dune erosion, while lower rock platforms are associated with more extensive dune erosion. This highlights the complex interaction between geological control and storm impacts, with implications for improved understanding of coastal resilience and storm-driven morphosedimentary dynamics in rock-fronted barrier systems.

Keywords: Geological Control · Coastal Barriers · Storm Impacts · XBeach

1 Introduction

Storm-induced morphological changes in coastal barriers are primarily determined by the interaction between the hydrodynamic forcing conditions and the mobile sediment. However, the presence of irregular non-erodible surfaces on rock fronted beaches influences nearshore hydrodynamics and morphodynamic processes [1, 2], resulting in spatially variable morphological changes [3, 4]. Process-based modelling is nowadays commonly used to predict storm-induced morphological changes at unconstrained coastal barriers, but there are still few studies for geologically controlled barriers. Therefore, exploring the influence of intertidal rock platform configurations on morphological responses during storms in such barriers through process-based morphodynamic modelling can help

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to understand spatially varying morphological changes in geologically controlled barrier settings.

Along the coastline of the Outer Hebrides (NW Scotland), a chain of barrier islands developed on a gently sloping undulated bedrock that extends from the coast to ~ 50 km offshore [5]. This coastline is exposed to frequent and extreme coastal storms [6], providing the ideal setting to investigate the understudied role of geological control on storm response in barriers positioned on top of bedrock surfaces. This work investigates storm-driven dune erosion for a range of schematic profiles representative of the Hebridean coastal barriers using the process-based XBeach model.

2 Methods

XBeach was implemented in 1D surfbeat mode to model the morphological response to storms on cross-shore profiles with varying rocky foreshore configurations. Boundary conditions were derived from SWAN, forced by buoy and tide gauge data from a storm event in February 2022 ($H_S \geq 12$ m, $T_p \geq 18$ s). The cross-shore profile was derived from the integration of EMODnet bathymetric data and RTK-DGNSS topographic surveys of pre- and post-storm barrier profiles. The control exerted by the natural bedrock and the schematic rock platforms was numerically implemented by: i) setting the bedrock as an unerodable layer; ii) increasing the wave dissipation through higher bed (c_f) and wave (f_w) friction coefficients in the rock sections; and iii) lowering the breaker index (γ) in the rock sections (Fig. 1a). The sandy part of the profile was set to default values.

The calibration of the bedrock-induced wave dissipation was conducted in two steps. First, the short-wave related friction f_w on bedrock surfaces was calibrated by an optimization routine through the comparison of modeled and observed incident-band nearshore wave heights in the intertidal beach profile. The observed nearshore wave data were obtained from pressure transducer measurements during a spring high-tidal cycle in February 2023. In the second calibration step, 81 combinations of different γ and c_f values on bedrock surfaces were tested for a profile where storm-induced morphological changes were observed during the February 2022 storm event (P_{N1}, Fig. 2). The γ and c_f combination that performed better in reproducing observed morphological changes was validated by comparison of the modelled storm response against observations at two alongshore adjacent profiles. After calibration and validation, four schematic profiles were developed by varying the position of an intertidal rock platform (P_{S1-S4}, Fig. 2). The platform geometry was kept constant, but its elevation was determined according to different tide levels (Fig. 1a), with higher elevations increasing the level of the geological constraint. The schematic cross-shore profiles are representative of existing barrier profiles in the Outer Hebrides (Fig. 1b,c).

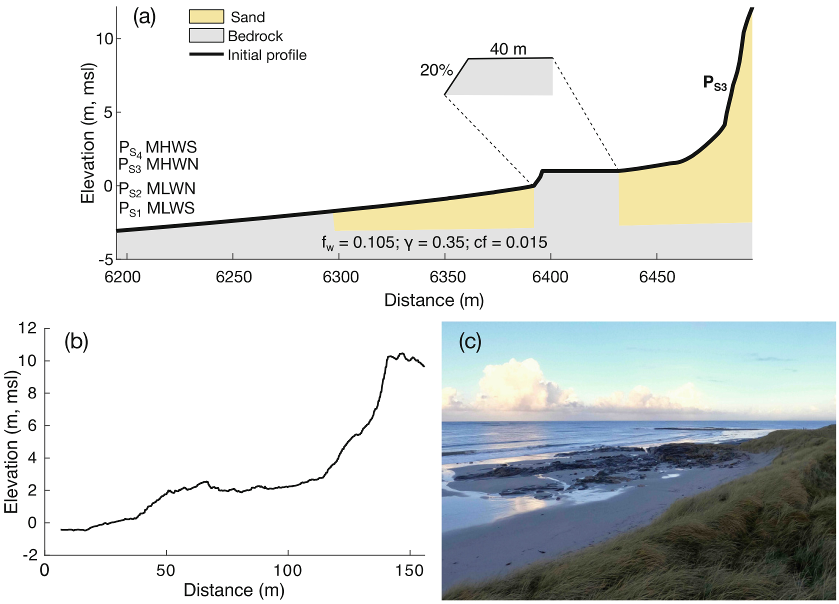

Fig. 1 (a) XBeach profile configuration and geometry of the schematic rock platform, for P_{S3}. (b) Example of a cross-shore profile with an intertidal rock platform in the Outer Hebrides. (c) Photograph of the example intertidal rock platform.

3 Results and Discussion

The predicted incident-band wave heights are in excellent agreement with the observations when f_w is set to 0.105 on the rocky profile sections. In the second calibration step, the combination of $c_f = 0.015$ and $\gamma = 0.35$ for the rock sections resulted in modelled morphological changes that closely matched the observed post-storm profile at P_{N1} and predicted muted morphological response at the adjacent profiles, consistent with field observations. These friction coefficients are within the range of values reported for hydrodynamic modelling with XBeach on reef and rock fronted coastlines [7, 8].

The morphological change predictions obtained using the schematic profiles, show that rock platforms with elevation above the mean sea level ($P_{S3–4}$) result in dampened dune erosion (Fig. 2), despite the extreme hydrodynamic forcing conditions. No significant reduction in dune erosion is predicted for P_{S1} and P_{S2}, which have rock platforms below this level. The elevation of the intertidal rock platform is found to be a key factor in controlling storm-induced barrier morphological change. This suggests that the relationship between the elevation of the intertidal rock platform and the total water level during the storm is a primary factor affecting storm impacts in rock fronted barrier sectors in the Outer Hebrides.

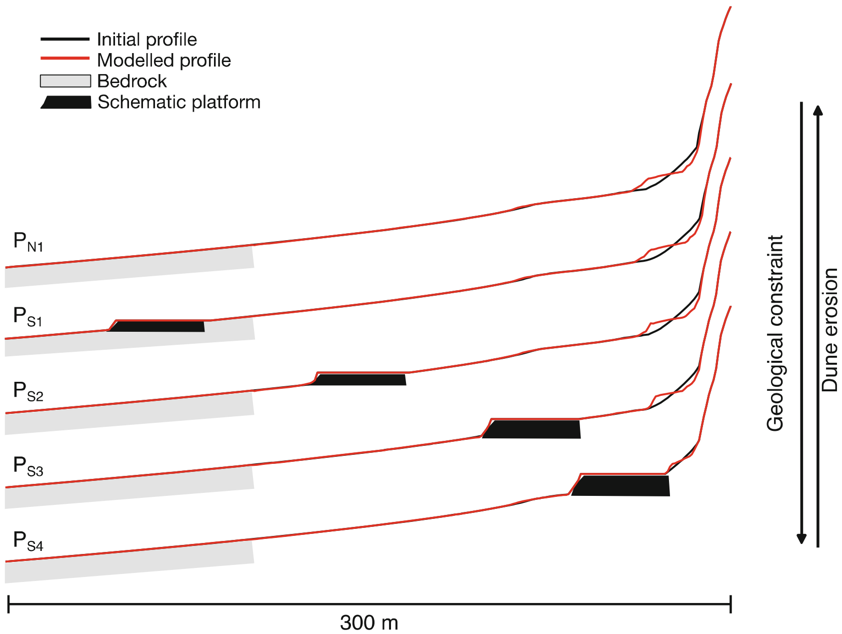

Fig. 2 Modelled storm response of profile P_{N1} (original profile) and the schematic profiles P_{S1}-P_{S4}.

4 Conclusion

This work demonstrates that XBeach can predict spatially variable storm-induced dune erosion during extreme storm events in a highly geologically controlled barrier once wave transformation on bedrock surfaces is calibrated. This enabled testing storm responses of both measured and schematic profiles to disentangle the influence of intertidal rock platforms on barrier morphodynamics during storm events. Model results indicate that increased geological control exerted by intertidal rock platforms at higher tidal elevations (above mean sea level for the tested conditions) contributes to lower storm-induced dune erosion, highlighting the interdependency between dynamic forcing and geomorphological characteristics in modulating storm impacts. Further research with different geological control configurations and forcing conditions will contribute to improved evaluation of the degree of geological control on storm-induced morphological changes of rock-fronted barriers.

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Risk Assessment for Rocky Cliffs: Application to the Coastal Area of Lagoa, Southern Portugal

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Abstract. Coastal areas are highly vulnerable to extreme events, particularly in rocky coastal environments where cliff collapse poses a significant risk to human occupation. This study presents a simplified method for assessing coastal risk at the top of rocky cliffs, integrating hazard and exposure into a single risk index. The methodology is based on the Coastal Risk Assessment Framework and incorporates hazard (inland extent of cliff mass movements) and exposure (land use) indices to calculate a Coastal Index (Ci). This approach was applied to the coastline of the municipality of Lagoa (Algarve, southern Portugal), which is characterised by indented rocky cliffs, pocket beaches, and subject to high touristic pressure. Risk maps were developed to determine the spatial variability, revealing a predominantly low to moderate risk along the coastline. However, 22% of the study area was identified as having high to very high coastal risk, particularly in areas with urban or touristic development close to the cliff edge. The method provides a straightforward tool for coastal management, enabling the identification of risk hotspots and the optimization of resource allocation for risk reduction.

Keywords: Mass Movements · Coastal Cliffs · Hazard · Land Use · Coastal Index

1 Introduction

Coastal areas are often densely populated while also exposed to extreme events that cause several hazards, the combination of which can lead to the occurrence of coastal risks. In rocky coasts, a key risk is the potential impact of cliff collapse on the existing human occupation. In contrast to sandy coasts, hazard zones cannot be defined based on the simple projection of shoreline change rates into the future, as even in cases of rocky coasts with low or very low average retreat rates, there is potential for occasional medium to large-scale mass movements to occur (Del Río and Gracia, 2009). Consequently, alternative approaches must be employed for cliffed coasts, reflecting the episodic occurrence of mass movements.

The majority of the existing studies that identify potential impacts of cliff movement on human occupation characterise the hazard, vulnerability and/or risk based on composite indexes (e.g. Del Río and Gracia., 2009; Nunes et al, 2009; Bergillos et al., 2022).

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These hazard indexes are typically the result of a combination of variables representing indirect factors (e.g. lithology, structure, wave exposure, cliff protection) that determine the alongshore variability of the hazard. However, they do not consider the cross-shore expression of the hazard as a function of the mass movement inland extension associated with different return periods. Other authors have defined the spatial distribution of the hazard based on statistical methods (e.g., Marques et al., 2011, 2013; Marques, 2018), encompassing a set of predisposing factors for cliff failure associated with the cliff's geology and geomorphology. The number of studies that address both the alongshore and cross-shore variability of the hazard remains limited, with many focusing on specific areas with detailed datasets (e.g. Penacho and Marques, 2023). Furthermore, there is a paucity of literature integrating both hazard and exposure to obtain the spatial distribution of the risks for the occupation of cliff tops (e.g., Del Río and Gracia, 2009).

The present study proposes a simplified risk assessment method for areas at the top of rocky cliffs, integrating hazard (as a function of the probability of cliff mass movements' inland extension) and exposure (as a function of the land use). The test area was the coastline of Lagoa council (Algarve, southern Portugal), an indented rocky coastline with pocket beaches, diverse land uses and subject to high touristic pressure (Fig. 1).

2 Methods

The methodology employed in this study is an adaptation of the Coastal Risk Assessment Framework (CRAF) proposed by Viavattene et al. (2018). Indexes related to hazard (H_i) and exposure (E_i) were used to calculate a coastal index (C_i), which serves to quantify the risk along the top of rocky cliffs. The application of these indexes to the coastal area of Lagoa council (Fig. 1) enabled the generation of risk maps, which illustrate the spatial variability of the risk. The C_i is obtained as follows:

$$C_i = (H_i * E_i)^{1/2} \quad (1)$$

The H_i ranges from 1 to 5, depending on the maximum inland extension of the cliff mass movements associated with different return periods (based on Teixeira, 2006), and also takes into account a legally established protection distance of 200 m from the cliff top, which is defined based on the potential for sinkhole collapse (Table 1). Return period estimations by Teixeira (2006) are based on the analysis of two datasets of mass movement width (inland extension) recorded along 46 km of rocky cliffs carved on Miocene calcarenites along the central Algarve coast. These comprise a nine-year-long field inventory (1995–2004) and a 44-year-long catalogue obtained from the analysis of aerial photographs (1947–1991). A total of 155 events with maximum mass movement widths of at least 4 m were considered for the statistical analysis. Power-law distributions were fitted to determine the relationships between return period and mass movement width (see Teixeira, 2006), thereby enabling the delineation of hazard zones according to the designated return periods intervals (Table 1).

The E_i is determined heuristically as a function of various land use types, defined in the 2018 national land use categorisation for Portugal (DGT, 2019), with a minimum mapping unit size of 1 ha, and a minimum spacing between mapping lines equal or greater than 20 m. The exposure, as a function of the land use classes, was also classified from 1 to 5 according to the severity of the possible impacts on people, economic activities and society (examples in Table 1). The resulting C_i index values obtained were divided into 4 classes from low to very high risk (Table 1).

Fig. 1. Location of the Lagoa municipality coastal area. The white diamond represents the location of the study area within the Iberian Peninsula (right panel), and the red rectangle refers to the area shown in Fig. 2, near Carvoeiro town. Image source: Google Earth, CNES/Airbus, June 2020.

Table 1. Hazard and exposure classes and assigned values as a function of the distance from the cliff top and land use. Risk classes as a function of the calculated C_i value.

Return period (years) - Distance from cliff top (m)	H_i	Land Use (examples)	E_i	Risk	C_i
[0–10] - [0, 23]	5	Continuous urban fabric	5	Very High	[4, 5]
]10–25] -]23, 35]	4	Discontinuous urban fabric	4	High	[3, 4[
]25–50] -]35, 48]	3	Road network and car parks	3	Moderate	[2, 3[
]50–100] -]48, 67]	2	Parks and gardens; Agricultural areas	2	Low	[1, 2[
$>$ *100* -]67, 200]	1	Bare rock; Wastelands; Sparse vegetation	1	No risk	0

3 Results and Discussion

The cross-shore distribution of the hazard is the same for the entire study area (Fig. 2a), as the hazard classes are a function of the landward retreat due to the mass movements, as determined by Teixeira (2006). This assumption considers the same likelihood of occurrence of mass movements for the entirety of Miocene rocky cliffs along the central Algarve. Therefore, the variability of the C_i for the coast of Lagoa council depends mainly on the variation in land use. The study area encompasses a wide range of land uses, being dominated by areas with very low exposure (bare rock), but including also moderate exposure (discontinuous urban) along sections of the cliff top area. However, there are areas of touristic agglomeration with consolidated urban uses, often along cliffs near to pocket beaches, which determine very high exposure levels (Fig. 2b). The resulting risk classes along the cliff edge are predominantly low to moderate (78%). Nevertheless, there are several risk hotspots (high to very high risk classes), which together represent 22% of the 13.5 km of coastline analysed. These include areas occupied by small towns (e.g. Carvoeiro; central part of Fig. 2c) or tourist resorts (e.g. Tivoli Carvoeiro Algarve Resort; eastern part of Fig. 2c). In total, 10 hotspots were identified, all near or at the edge of the cliffs, with coastline lengths ranging from about 100 m to 500 m.

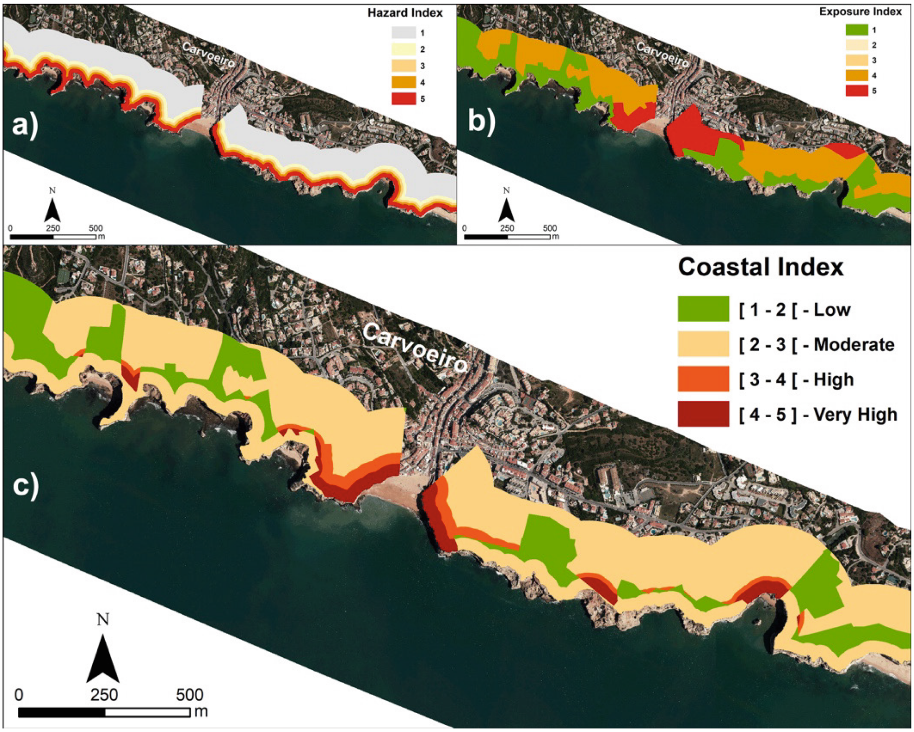

Fig. 2. Coastal risk for the Carvoeiro town, including: a) hazard index, b) exposure index and c) coastal index. Aerial image from 2018 provided by DGT.

Methods based on indexes are the most common approach used to assess hazard and risk along rocky cliff coasts. However, most of them do not provide an analysis of risk based on the probabilistic assessment of hazards, and are limited in their ability to provide a temporally constrained analysis that better supports priority setting. These methods often require the calculation and combination of a large number of variables to derive a composite risk index (for example, 11 physical and 6 socioeconomic variables proposed by Del Rio and Gracia, 2009), which can hinder their use in areas with scarce data. The relative importance of each variable in the final risk assessment is often unknown, and weighting factors have be defined for each variable used in each application, increasing the complexity and reducing the transferability of the methods.

The method presented here provides an integrated risk zonation of coastal areas adjacent to the top of rocky cliffs, allowing the definition of critical (priority) areas. It prioritises the cross-shore differentiation of the hazard as a function of the return period of the hazardous event (mass movement), while the exposure is considered using a simple but integrative parameter (land use). This method provides a straightforward and efficient approach for evaluating and ranking risk levels in rocky coastal regions with similar geomorphological and hydrodynamic characteristics. Therefore, it is a useful and simple tool for coastal management purposes, allowing the optimisation of resources and a rapid decision-making process regarding the areas that should be prioritised for coastal management interventions. The method can be easily applied to other rocky coastal areas, provided that hazard zones are or can be readily defined and land use maps can be meaningfully converted into exposure classes.

4 Conclusions

This work presents a novel yet simple method to characterise and rank coastal risks at the top of rocky cliffs, integrating hazard and exposure in a straightforward index. The application of the method to the coastline of Lagoa council allowed the identification of 10 coastal hotspots (high and very high risk) near the cliff edge, mostly associated with villages or touristic resorts. This approach can be used for management purposes and to optimise the use of resources in rocky coastal zones.

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Unravelling the Response of the Guadiana Ebb-Tidal Delta to Extreme Wave Events

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Abstract. This study investigates the morphodynamic response of the Guadiana ebb-tidal delta to extreme wave storms using a process-based numerical model. Field data including wave climate, wind and bathymetry were integrated into the Delft3D model, calibrated and validated with hydrodynamic data collected at the lower estuary in 2013, 2015 and 2023 and bathymetric maps of the ebb delta from 2016 and 2017. The analysis focuses on the impact of Storm Emma (February-March 2018), characterised maximum wave height up to 7.1 m. Results show that Emma induced a significant shift in sediment dynamics, causing retreat and erosion of the updrift shoal complex (with a net sediment volume loss of 2.40%), sediment transfer to the downdrift complex (that gained sediment volume of 0.32%), and channel rotation.. These changes contrast with the seaward growth of the shoal under mild conditions observed during non-extreme conditions, as between 2016 and 2017. The results highlight the importance that large extreme wave events can have on the morphodynamic evolution of ebb tidal deltas.

Keywords: numerical model · ebb tidal delta · Emma storm · morphology

1 Introduction

Ebb-tidal deltas are among the most dynamic coastal areas in the world. Understanding their morphodynamics under various forcing conditions, such as wind waves, tidal flows or littoral drift, has become increasingly important for effective management. This need arises from growing pressures exerted by climate change and human interventions, such as development of navigation channels, which have significantly threatened their environmental quality in recent decades. This study aims to characterise the morphodynamic response of the Guadiana ebb-tidal delta (GETD) to extreme wave storms using a process-based numerical model. The results are crucial for understanding how changes in the frequency and intensity of these extreme events may affect its morphodynamic evolution in the coming decades.

The GETD is a mixed-energy, tide-dominated delta on the southern border between Spain and Portugal. In the region, tides are semidiurnal with a mean tidal range of 2 m.

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The offshore wave climate is dominated by W–SW waves (71% of occurrences) and SE sea waves (23% of occurrences) of moderate energy, with yearly averaged significant wave height of 1 m and peak period of 8.2 s [1]. The littoral sand transport in the area is eastward, feeding the delta by an average of 100 Mm^3/year, with little contribution from the Guadiana River.

The delta (Fig. 1) typically consists of a main inlet channel and outer ebb shoal featuring subparallel lobed swash bars, flanked by shallower areas affected by waves. The updrift area consists of a narrow and straight lateral bar, while the downdrift area consists of a broad complex, which is the remnant of the historic delta (before the jetty was built), which widespread erosion nourishes adjacent beaches [2].

Storm Emma made landfall in the southwest of the Iberian Peninsula on 28 February 2018 and lasted about 4 days during a spring tide period. Propagating in a WNW direction, the storm reached a maximum wave height of 7.1 m, with a mean wave height of 4.1 m, causing beach erosion and damage to several coastal infrastructures along the coastline of the Gulf of Cádiz.

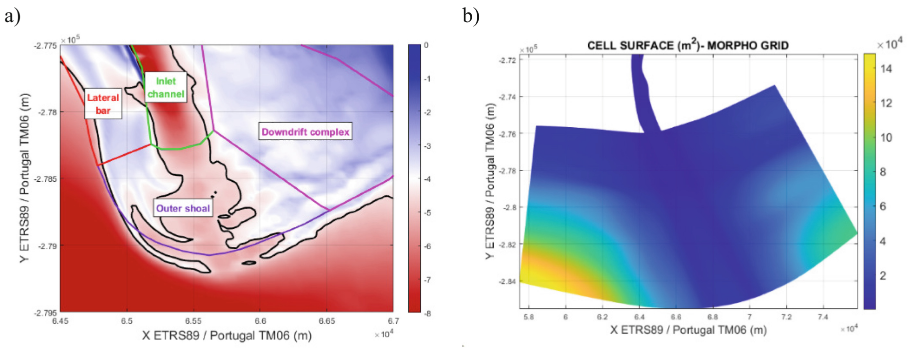

Fig. 1. (a) Initial bathymetric grid (2016). The figure shows areas of motion transfer according to [3]: updrift lateral bar, outer shoal, inlet channel and downdrift complex. (b) Cell surface (m^2) of the morphological grid.

2 Methods

2.1 Field Data

Wave observations recorded every three hours were retrieved from the Faro buoy (IH - Instituto Hidrográfico de Portugal), located at 50 km west of the study site. Gaps in the hourly time-series were replaced by hindcasts extracted nearby from the SIMAR (point 1049047) numerical model (Spanish National Port Authority). Significant wave heights from the model (Hs*) were corrected using the correlation Eq. (1) obtained through comparison with available buoy observations (Hs) for the period 1958–2024:

$$H_s^* = 0.987 \cdot H_s + 0.468 \tag{1}$$

Hourly wind data were obtained from the SIMAR model. The daily average Guadiana River discharge was obtained from a hydrographic station (Pulo do Lobo) near the estuary head [4]. Both data for 2016–2018.

Hydrodynamic observations included water level and depth averaged velocities collected at the lower estuary (i.e., 4 km upstream from the mouth) in 2013, 2015 and 2023 at 15 min intervals with an Acoustic Doppler Current Profiler (ADCP). Bathymetric data were collected (in RTK mode) in June 2016 and 2017 using a single beam echo sounder along parallel transect of 50 m intervals. The water depths were tide-corrected and referenced to the mean sea level (MSL) in ETRS89, Portugal TM06 coordinate system (Fig. 1a).

2.2 Numerical Model

The Delft3D model was implemented at the study site to simulate the morphodynamics of the GETD, using both the hydrodynamic (Flow) and wave propagation (Wave) modules. The simulations were carried out in two dimensions, solving the depth-averaged flow. The van Rijn [1993] equations were used to calculate the suspended and bedload sediment transport due to waves and currents.

The grid of the model covered the ebb-tidal delta and lower estuary stretch lying from the mouth to 7 km upstream (Fig. 1b). A non-uniform grid with minimum grid size of 20 × 20 m was used [6] over the ebb delta. The boundary conditions were: (1) the fourteen main tidal constituents for the offshore boundary, (2) Neumann conditions for the lateral cross-shore boundaries, and (3) depth averaged velocities at the upstream boundary. These velocities were obtained from prior hydrodynamic simulations carried out on a different grid covering the complete estuary (from the head at Mértola to 10 km offshore) that included the Guadiana River discharge.

The numerical model was calibrated and validated for hydrodynamics and calibrated morphodynamics.

For the former, water level and depth-averaged velocity data from 2015 [5] and 2023 were used (Fig. 2). The validation was performed using data from a period of high river discharge in 2013, which peaked at 2,331 m^3/s.

The results of the hydrodynamic validation for the depth averaged velocity along the estuary channel are excellent. The results were observed for the period 01 March 2013 to 01 May 2013 with a root mean square error of 0.28 m/s, a correlation coefficient of 0.93 and a skill score of 0.91 for the northward velocity and 0.07 m/s, 0.93 and 0.89 for the eastward velocity.

For the morphodynamic calibration, bathymetric maps of the GETD from 2016 and 2017 were used, simulating the period between the two field surveys and comparing predicted and observed bed levels. This period was characterized by a wave climate with mean wave energy consistent with the historical data and no major storms occurred. The BSS (Brier Skill Score) index [6] was used to quantify the agreement between observations and model results, complemented by the adjustment of the mean-squared error skill score [7].

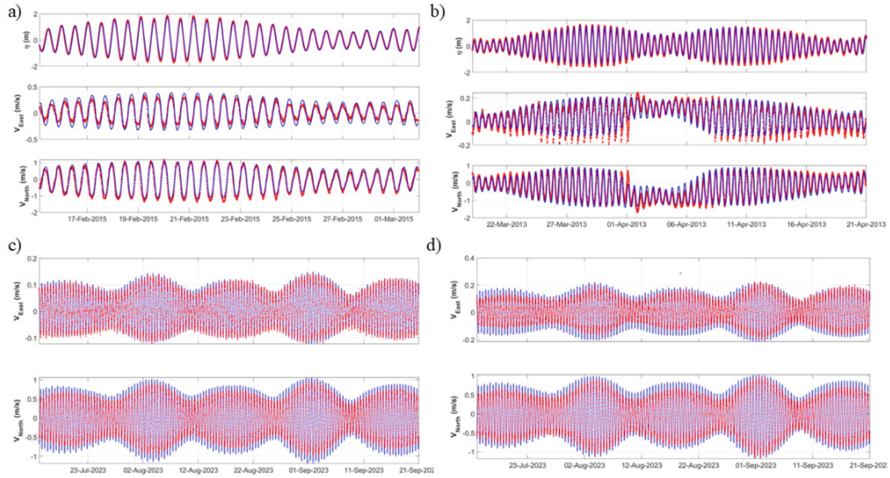

Fig. 2. Hydrodynamic model calibration and validation results. ADCP field data (blue) and DELFT3D model data (red) are compared with water level η (m), north velocity, and east velocity. (a) Model calibration (Feb 15, 2015 - Mar 02, 2015). (b) Strong river discharge event (Mar 01, 2013 - May 01, 2013). (c, d) Model Jul 14, 2023 - Sep 15, 2023.

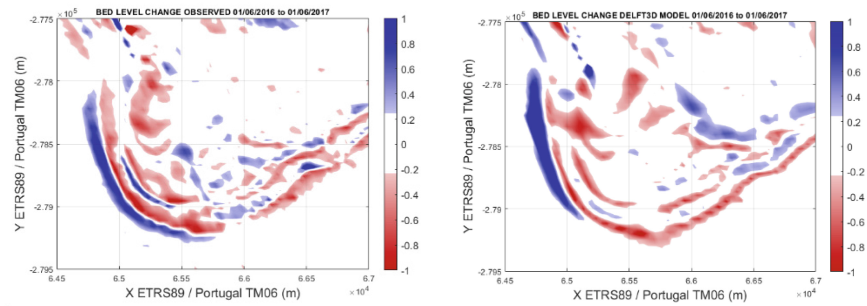

Fig. 3. Difference in bottom depth (in meters) between 2017 and 2016 from observations (left) and simulations (right). The color indicates changes in bed elevation > 0.2 m Negative values indicate erosion (red), while positive results indicate sedimentation (blue).

For the morphodynamic calibration, a BSS of 0.59 (good) was obtained for the GETD (Fig. 3). If only grid cells with bed level changes > 0.5 m are considered, the BSS result is 0.84 (excellent, according to the Sutherland scale). Furthermore, the erosion and deposition patterns observed during 2016–2017 period are qualitatively well captured (Fig. 3), although the erosion processes are slightly underestimated.

3 Results

The morphodynamic behaviour observed between 2016 and 2017 corresponds to a typical year with non-extreme energy conditions [3]. Broadly, it is characterized by a seaward growth of the outer shoal and landward retreat of the downdrift complex. In contrast, run between June 2017 and June 2018 show that the Emma storm produced a markedly different pattern of erosion and sedimentation (Fig. 4). During the storm, the updrift flank of the delta retreated, and sediment was transferred to the downdrift complex that extended offshore (Fig. 4). There was also a noticeable shift (up to 30 m) and clockwise rotation of the channel of about 6º (dashed lines Fig. 4).

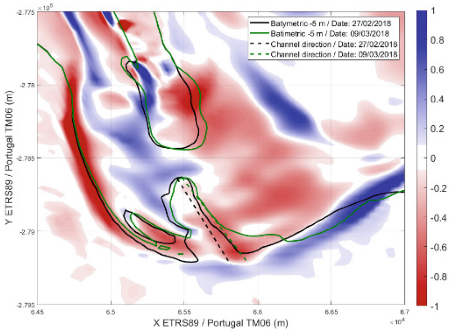

Fig. 4. Result of the Delft3D model. Bed level change between June 2017 and June 2018, showing the influence of Emma Storm. Erosion in red and sedimentation in blue. The continuous lines represent the -5m depth contours. The black lines correspond pre-Emma (27/02/2018) while the green lines represent, after the Emma Storm (09/03/2018). The dashed lines indicate the navigation channel direction for both years.

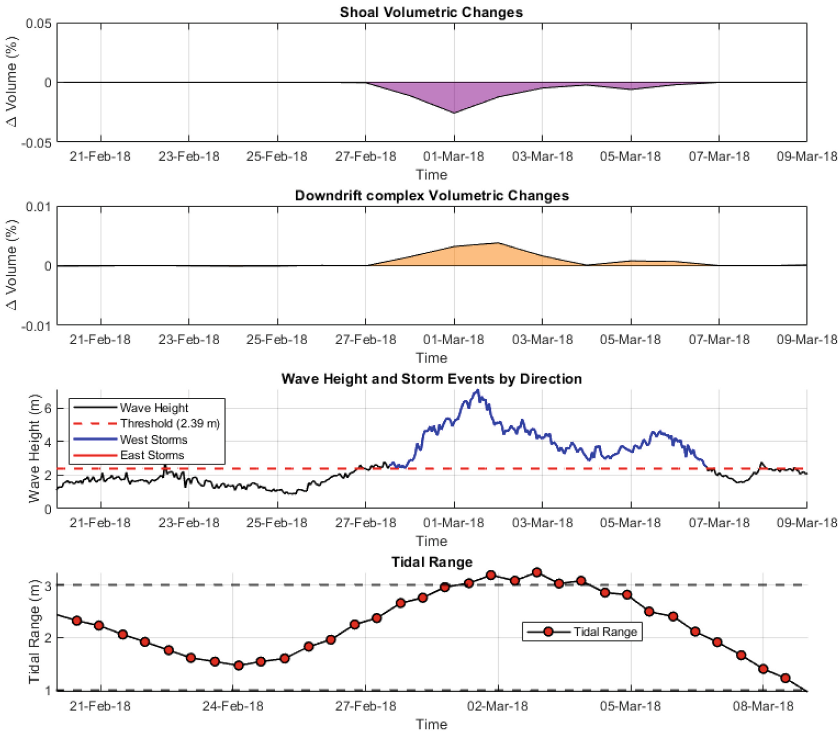

Fig. 5. From top to bottom: (1) Volumetric change in the shoal complex, (2) Volumetric change in the downdrift complex, (3) Significant wave height, (4) The tidal range.

Average daily volume changes in the GETD analysis areas (shoal and downdrift complex) were calculated, showing that the largest volume changes (increase/decrease) occurred during the Emma storm (Fig. 5). The simulation revealed a total net sediment volume loss of 2.40% in the updrift area (Fig. 5a) during Storm Emma (February-March 2018), offset by an increase of 0.32% in the downdrift complex (orange area, Fig. 5). These quantitative results are consistent with the qualitative trends observed in Fig. 4. In addition, the data show that sediment transport is significantly correlated with storm events. Figure 5 clearly shows that volume changes coincide with both storm events and periods when tidal conditions deviate from the average range (more than 3m above the average maximum range).

4 Conclusions

This study analyses the impact of the Emma storm on the mophodynamics of the GETD. Numerical model results show that Emma caused large areas of erosion and deposition in the delta, with patterns that contrast with those observed under mild wave energy conditions. Overall, the storm induced a clockwise rotation of the entire delta (with retreat of the west flank and accretion of the eastern flank), including the navigation channel, associated to significant changes in sediment volume across the main features of the delta.

These findings have critical implications for the effective management of the delta, its navigational channel and adjacent beaches, particularly in the context of increasing intensity and frequency of extreme wave events driven by climate change. Furthermore, this study highlights the value of numerical modelling as a robust tool for understanding and predicting the complex dynamics of the GETD.

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