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Modeling of Coastal Erosion in Exposed and Groin-Protected Steep Beaches

Juan L. Garzon[1]; Óscar Ferreira[2]; and Theocharis A. Plomaritis[3]

Abstract: Process-based models are suitable tools for reproducing storm-driven erosion. However, their performance has been mainly examined on mild-slope sandy beaches and their use on steep beaches still represents a challenge. Here, open-source process-based model XBeach experiments were combined with topographical measurements collected for two storms (16- and 5-year return period) to obtain a reliable model. The model parameters "facua" (parameterized wave asymmetry and skewness sediment transport component), "bermslope" (upslope transport term for semireflective beaches), and "wetslope" (critical avalanching submerged slope) were utilized for calibration and validation. The 16-year storm simulations on an exposed beach revealed that whether bermslope increased and "facua" must be reduced, and vice versa, to properly simulate erosion. Adding bermslope provided excellent results for these storms when using facua and wetslope values close to the recommended values. In a groin-protected site, XBeach was successfully calibrated and validated for the tested storms using these parameters, although with different values. These experiments demonstrated that the appropriate use of these parameters can satisfactorily simulate morphological changes on steep beaches for different hydrodynamic conditions and coastal settings (exposed and groin protected).
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Introduction

Sandy coasts are among the most populated areas worldwide and they host a large number of socioeconomic activities. However, these environments are susceptible to the impact of coastal storms, with storm surges and waves generated during energetic events causing severe erosion and shoreline retreat. Moreover, this problem might be exacerbated by rising sea levels and changes in storminess. Under these threats, predicting erosion due to extreme oceanic events is essential to improve coastal management and implement mitigation measures (e.g., early warning systems) that contribute to avoiding or minimizing their effects on socioeconomic activities and ecosystem services. Among the different alternatives to support engineers and decision-makers, morphodynamic numerical models are increasing in popularity. For instance, the open-source process-based model XBeach (Roelvink et al. 2009) has been applied and validated in many sandy beaches worldwide impacted by severe tropical and extratropical storms. This model solves wave breaking, surf and swash zone processes, dune erosion, and overwashing in a one-dimensional (1D) or a horizontally two-dimensional (2D) computational grid under the assumption of a saturated surf zone, mainly occurring in dissipative beaches.

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Dissipative beaches present a mild slope in the intertidal region, and wave processes are dominated by skewed and asymmetric short-crested waves, undertow, and infragravity waves. Several modeling studies have focused on these types of environments (e.g., McCall et al. 2010; van der Lugt et al. 2019) demonstrating that, after a calibration process, XBeach can properly simulate coastal morphological changes of the subaerial beach during storm events. On the other hand, the storm-induced morphological response in less dissipative beaches has not been widely numerically investigated yet. Steep sandy beaches can be found in many regions, including Portugal, New Zealand, the southeastern coast of Australia, and the Californian coast, and yet the modeling of coastal erosion in intermediate and reflective sandy beaches is still an ongoing challenge (Roelvink and Costas 2017). In reflective beaches, the energy of the incident waves and the subharmonic oscillations may dominate in the inner surf and swash zone against the undertow and the infragravity waves. Thus, modeling of the subaerial profile morphology without considering the evolution and decay of individual waves becomes complicated at these beaches. Orzech et al. (2011) stated that the XBeach (surfbeat) underestimates the uprush sediment transport in the swash zone at steep beaches, relative to the offshore transport induced by the backwash, leading to excessive removal of sediment in the beach face. Consequently, special caution is required for the model parametrization when developing prediction systems on nondissipative beaches.

In earlier studies (Simmons et al. 2019; Vousdoukas et al. 2012b), erosion overestimation was partially overcome by increasing the parameterized wave asymmetry and skewness sediment transport component ("facua"). This enhances the onshore sediment transport that counteracts the offshore one induced by the wave rundown, promoting a better calibration for beach erosion. In line with this approach, Elsayed and Oumeraci (2017) found a power function relation between the average slope steepness and facua. Nevertheless, Simmons et al. (2019) stated that increasing facua improves the prediction in the dune and berm but unrealistically flattens the modeled beach profile around the waterline. They noticed that in steep profiles, the measured poststorm profile retreated but maintained a similar prestorm slope. To reproduce this observed behavior, Roelvink and Costas (2017) proposed a pragmatic approach where the beach face slope is forced to stay close to a given slope, the "bermslope." Therefore, an onshore transport term that is proportional to the difference between the actual slope and a prescribed bermslope is added to the swash zone. While this transport term was initially thought to improve the reliability of the XBeach model in the long-term simulations, Roelvink et al. (2019) demonstrated that this new addition also has a beneficial effect on the profile evolution during storm events on steep beaches. Moreover, they suggested that bermslope could minimize the importance of other slope parameters implemented in the model, such as "wetslope," which establishes the critical bed-slope of the wet profile before the initiation of avalanching. Cho et al. (2019) declared that XBeach is more sensitive to changes in wetslope values in a steep profile than in a mild profile, and, hence, the selection of this parameter should be carefully considered in these beaches.

In terms of computational effort, using a 1D approach to calibrate a model instead of a 2D model would be more efficient since it would allow for a more rapid assessment of all free model parameters, especially for highly complex, process-based models. The downside of this approach is that the findings of a 1D calibration model might not be directly applied to a detailed 2D model. Cross-shore profile models have the inherent limitation of longshore uniformity, and they are not capable of capturing the effects of longshore transport gradients. Conversely, the 2D models incorporate longshore variations, and they are not limited to straight-line coastal systems, being able to represent diverse coastal geometries (e.g., Dissanayake et al. 2014; McCall et al. 2010; Plomaritis et al. 2018; van der Lugt et al. 2019). A few studies (Dissanayake et al. 2014; Harter and Figlus 2017) have conducted a more efficient approach, optimizing a 1D XBeach model and then transferring the optimum settings to a larger 2D XBeach model. This practice might avoid excessive computational burdens when calibrating a model, and yet the downside of such an approach was not fully investigated.

While process-based models seek to explicitly represent the crucial physical dynamics, in practice they include semiempirical parameterizations to improve their efficiency. This results in a large number of free-model parameters to calibrate, especially for coastal morphologies where research efforts have been less intense (e.g., steep beaches). The constant evolution of the models implies the necessity of continuous calibration and validation. Also, calibration parameters vary according to the specific characteristics of each site. The present study has a twofold objective: first, to perform a sensitivity analysis of the main morphological parameters used for XBeach calibration (facua, bermslope, and wetslope), and second, to use these results to calibrate and validate XBeach for two storm events with different severity at two steep beaches with different levels of human intervention. The results will contribute to obtaining better model performances in such environments. Moreover, in cases where the available data for model calibration and validation are limited, recommendations for the model implementation are indicated.

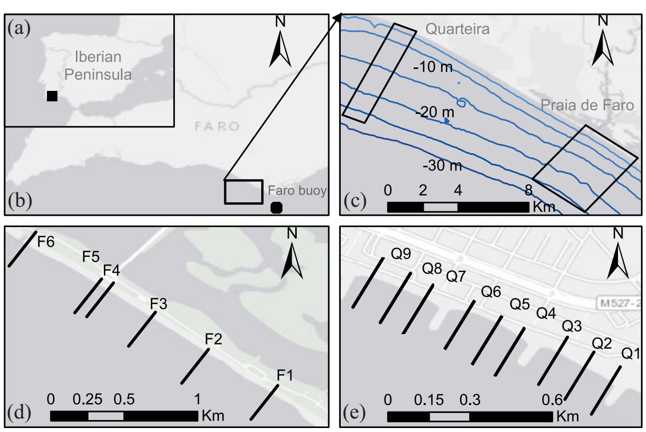

Fig. 1. Study areas: (a) Iberian Peninsula with the marker indicating the study area; (b) study area location within the Portuguese southern coast; (c) location of the Quarteira and Praia de Faro grid models; (d) Praia de Faro study area; and (e) three beach segments in the Quarteira study area limited by the perpendicular groins. The black lines indicate the cross-shore profiles analyzed. (Base map sources: Esri, HERE, Garmin, OpenStreetMap contributors, and the GIS user community.)

Study Area

Praia de Faro

Praia de Faro is a sandy beach located in the barrier island system of Ria Formosa, on the southern Portuguese coast [Figs. 1(a–c)]. The barrier splits the Atlantic Ocean on the front side from a coastal lagoon on the backside [Fig. 1(d)]. The study site is an elongated peninsula orientated 130° approximately (measure from the north). This beach is subject to significant urban development pressure, and the oceanfront is partially stabilized with rocks/walls or naturally protected by a dune. The dune morphology varies alongshore with higher robustness and elevation [7–8 m above mean sea level (MSL)] at the western portion of the study area [F6 in Fig. 1(d)], while at the central and eastern part, the dune is lower (6–7 m above MSL) and weaker. The central part, F4 and F5 in Fig. 1(d), is periodically overtopped during spring tides or storm conditions (Ferreira et al. 2019; Matias et al. 2010). The site presents a subtidal terrace and steep beach face, with an average slope of around 0.10 (Almeida et al. 2012; Vousdoukas et al. 2012a). In previous studies, such as Ferreira et al. (2016), this site has been classified as reflective during calm conditions and intermediate during energetic conditions with the formation of a longshore bar. A beach berm can be normally found, except after very energetic storms, with variable widths ranging from less than 15 m to more than 40 m (Ferreira et al. 2016). The study area responds rapidly to storm events and variations of the wave forces, and the beach can regain a large part of the sediment after storm events in days/weeks. Moreover, the site is characterized by the presence of multiple highly dynamic beach cusps at the lower-beach face that interact with the more persistent upper-beach face cusps (Vousdoukas et al. 2012a). Sediments are medium to very coarse, moderately well sorted sands with a median (d_{50}) of around 500 μm and d_{90} around of 2,000 μm (Vousdoukas et al. 2012b).

Quarteira

The town of Quarteira is located 10 km northwest from Praia de Faro [Fig. 1(c)]. The analyzed sector consists of a set of three sandy beaches with a total longshore length of 900 m. The main orientation of the coastline is 120°N, and the average beach slope is 0.10. Sediment grain size is slightly finer than in Praia de Faro, and d_{50} and d_{90} are 485 and 900 μm, respectively. The three beaches are laterally limited by 150 m-long rocky groins [Fig. 1(e)]. These groins make the three beaches behave like "man-made pocket beaches" subject to beach rotation as a function of wave direction. During the dominant conditions, the groins maintain the sediment in the system; however, during very energetic conditions, the sediment can fall outside of the system. Beach nourishments have been performed in the area to guarantee a reasonable beach width for bathing conditions, with a total of 360,000 m^3 placed in 1998 (Pinto et al. 2018). At the backside, the beach is limited by a long promenade with an elevation ranging from 6 to 8 m. While Quarteira represents a relevant touristic destination in Portugal, the beach morphodynamic has been poorly investigated.

Methods

Storm Events

Two storms impacting the area have been considered for analysis. Storm Emma, in March 2018, was a severe storm that traveled toward the northeast (Ferreira et al. 2019). The maximum significant wave height, Hs, during this storm was 6.55 m, with a peak period and direction of 13 s and 240°N, respectively [Fig. 2(a)]. Moreover, the timing of the storm matched with a spring tide, exacerbating the impact of the storm. The wave characteristics were measured at the Faro buoy and the water levels were extracted from the tidal gage of Huelva (Spain). Large damages were reported after the storm, especially in Praia de Faro (Ferreira et al. 2019). In December 2019, two consecutive storms hit the area, Storm Daniel (December 16) and Storm Elsa (December 19–20). These storms traveled across the North Atlantic from east to west, and their effects were widely felt in several Western European countries. Storm Elsa created Hs up to 5.15 m and a 11-s peak period at the Faro buoy [Fig. 2(b)]. This storm coincided with neap tides, probably reducing the negative erosive effects of the storm. Maximum Hs and peak period during Storm Daniel were 3.85 m and 9 s, respectively.

Based on the analysis of Pires (1998), Storm Emma corresponds to a 16-year storm (Ferreira et al. 2019), Elsa is a 5-year storm, and Daniel is a 1-year storm. Moreover, at Praia de Faro, during Storm Emma, the collision regime was observed in sections where the dune system is higher, while in sections where the dune is weaker and lower, overwash occurred. Storm Elsa caused mainly the swash regime; the collision regime was only observed in sections with a limited berm, and only the swash regime occurred during Storm Daniel. Therefore, for the southern Portuguese coast, Storms Emma, Elsa, and Daniel can be defined as high-energy, mid-energy, and low-energy events, respectively.

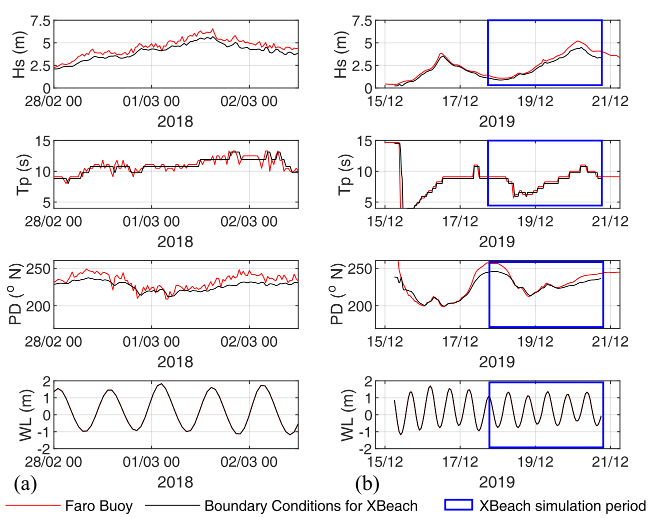

Fig. 2. Storm data: (a) hydrodynamic data measured during Storm Emma 2018; and (b) wave conditions provided by the wave prediction system of Puertos del Estado during Storms Daniel and Elsa 2019 (Faro buoy was not recording) and the water level measured at Huelva.

Morphological Data Set

To assess the ability of XBeach to model morphological changes during those storms, several topographic data sets were collected (Table 1). At Praia de Faro, after the peak of Storm Emma, on March 2, 2018, five profiles, F2–F6 [Fig. 1(d)], were surveyed with a DGPS (differential global positioning system). Within the COSMO program (PROGRAMA COSMO n.d.), an unmanned aerial vehicle (UAV) survey and a bathymetric survey were conducted at Praia de Faro in October 2018. The surveys covered the entire study site, including the nearshore area (13.5 m below MSL), beach face, dune system, and the urbanized area. The mean vertical error of the October 2018 survey along five profiles ranged between 0.14 and 0.20 m, considering the DGPS survey as the benchmark. Finally, another survey was conducted on December 20, 2019, to measure the elevation of four profiles (F1, F2, F3, and F5) after Storm Elsa.

On the Quarteira site, three surveys were conducted. First, on May 28, 2019, a Mavic 2 Pro UAV, was used to obtain a digital elevation model (DEM) and orthophoto map of the study area (Table 1). A total of 45 ground control points were marked at the fixed structures and at the beach to build the DEM. The elevation of the DEM was compared against four cross-shore profiles measured, and the estimated by root mean square error (RMSE) for the entire area was 0.09 m. The built DEM presented a resolution of 0.014 m, while the orthophoto had less than 1 cm of resolution. Second, two consecutive surveys were performed by using DGPS along nine profiles [Fig. 1(e)], on December 17, 2019, before Storm Elsa, and December 20, 2019, after Storm Elsa.

Two complementary sources were utilized to extract the elevation of the sea bottom in offshore areas of the model domains. The Agência Portuguesa do Ambiente (APA) surveyed the nearshore areas of the Quarteira site in 2018. The processed information covers from −1 to −8 m MSL. Moreover, a regional bathymetry of the entire southern Portuguese continental shelf was extracted from MIRONE (a Windows MATLAB-based framework tool) (Luis 2007) to cover the deepest region of the grid models. Both data sets have a resolution of 10 m.

Table 1. Topobathymetric dataset sources and date of acquisition. All sources were referred to MSL

Data acquisition methodology	Survey date	Profiles
Praia de Faro		
Walking DGPS topographic profiles	March 2, 2018	F2, F3, F4, F5, F6
Unmanned aerial vehicle (COSMO program)	October 2018	All
Bathymetry survey (COSMO program)	October 2018	Not applicable
Walking DGPS topographic profiles	December 20, 2019	F1, F2, F3, F5
Quarteira		
APA bathymetric survey	2018	Not applicable
Unmanned aerial vehicle	May 28, 2019	All
Walking DGPS topographic profiles	December 17, 2019	Q1–Q9
Walking DGPS topographic profiles	December 20, 2019	Q1–Q9

The comparison of the different profiles measured along Praia de Faro [Fig. 1(d)], together with those reported in Ferreira et al. (2019) and Garzon et al. (2020), allowed defining a fully developed-berm and a weak-berm profile, which are representative of this site. The first one, with a beach face slope of 0.13, had a well developed berm around the 4.4 m elevation, and the dune toe was found at 5 m [Fig. 3(a)]. The second profile displayed a beach face slope of 0.12, and the dune toe was located at 4.6 m. The berm of this profile was less marked than the previous profile and was therefore named the weak berm [Fig. 3(b)]. The vertical datum of the aforementioned elevation data were MSL as well.

XBeach Model Setup

The Praia de Faro 2D grid had an extension of 3,000 m longshore and 3,900 m cross-shore [Fig. 1(c)]. The numerical grid, with a variable longshore and cross-shore grid cell spacing, was built using the OpenEarth tool (Van Koningsveld et al. 2010). The grid optimization and interpolation were made based on the bathymetry data from the COSMO program survey (PROGRAMA COSMO n.d.), and the continental shelf referred to MSL. The minimum cross-shore and alongshore resolution in the sub-aerial beach were 2 and 10 m, respectively. Using satellite imagery available via Google Earth, parking lots, infrastructures, and building locations were identified and superimposed on the grid. At those locations, grid cells were set as a nonerodible layer. Therefore, these grid cells cannot be eroded or destroyed. This has important implications for Praia de Faro, where the seawall impedes erosion to reach the urbanized areas during severe storms (Ferreira et al. 2019). The 1D simulations were performed in cross-shore profiles extracted from the 2D grid at specific locations (F2, F3, F4, F5, F6), and thus, they maintained the same cross-shore resolution of the 2D grid model.

In Quarteira, two 2D grids were built using the OpenEarth tool. These grids shared geometry, domain, and resolution but differed in the intertidal and the dry region elevation to account for two different initial topographies. Regarding the topography, two data sets were used: (1) the 2D unmanned aerial survey of May 28, 2019 (hereafter the Quarteira May grid), and (2) interpolation of the nine profiles measured on December 17, 2019 (hereafter the "Quarteira December grid"), into a 2D elevation model of the dry beach combined with the elevation of the groins measured in the May 2019 survey. The dimension of the grids was 1,100 m longshore by 5,800 m cross-shore [Fig. 1(c)]. The grids presented a variable resolution with a minimum resolution of 2 and 5 m in the cross-shore and longshore directions, respectively. The longshore resolution was reduced to better capture the groin geometry. The nearshore bathymetry measured by APA and the regional bathymetry of the continental shelf were merged to cover the offshore and nearshore areas. Rocky groins and infrastructures determined as nonerodible in the model were identified from the orthophoto. The grid model elevation was referred to MSL.

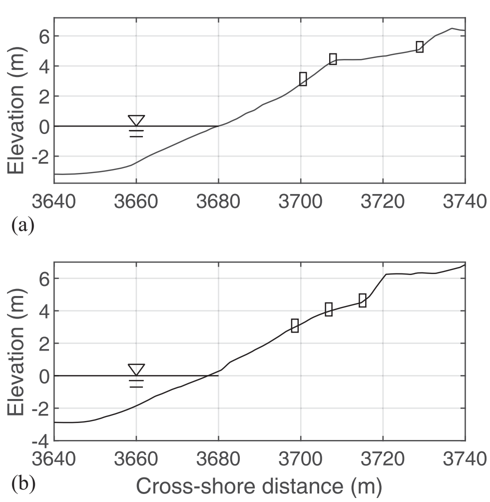

Fig. 3. One-dimensional profiles evaluated in the sensitivity analysis: (a) full-berm profile; and (b) weak-berm profile. The squares represent the displacement analysis location, with the upper one representing the dune toe at both profiles, the intermediate one the berm crest, and the lower one the 3-m MSL elevation (landward beach face).

This study used the XBeach X 1.23.5526 version with lateral Neumann conditions in the nonlinear shallow water equations and cyclic wave boundary conditions. The "single_dir" option was selected to simulate the propagation of the directionally spread short-waves group in the 1D and 2D models. In the 2D approach, the mean wave direction was intermittently computed using the stationary solver within XBeach, and then it propagated the wave energy along these directions. Thus, it preserved the groupness of the wave, leading to higher forcing on the infragravity waves (Roelvink et al. 2018). In the 1D approach, "single_dir" used a single-direction bin, considering waves reaching normally to the coast and ignoring refraction (Deltares 2018). To support transferability, many of the XBeach free parameters that can impact the ability of the model to predict morphological changes were either maintained in their default value or substituted by values reported in the literature (Table 2). For instance, in the absence of wave measurements in the surf zone, the breaker parameter, "gamma," was set to 0.56, as suggested by Callaghan et al. (2013). The parameters "gamma" (maximum ratio wave height to water depth) and "beta" (the breaker slope of the roller) were set to 2.364 and 0.138, respectively, following the values reported by Do et al. (2018), a study that investigated the modeling of dune erosion. To reduce the number of parameters to calibrate, the Manning's coefficient associated with bed roughness was based on land-cover classification for sandy sediment (Garzon and Ferreira 2016; van der Lugt et al. 2019). Also, a morphological acceleration factor of 10 was applied following previous studies, such as McCall et al. (2010).

A SWAN model (Booij et al. 1999) was created for the southern Portuguese coast to propagate the wave conditions from the Faro buoy to the study sites [Fig. 1(b)]. The grid was curvilinear to match the variations of the bathymetry, with a varying resolution (from a few km to hundreds of m). SWAN outputs from the nonstationary computations were extracted at the offshore boundary of the XBeach computational grids, between water depths of 25 and 30 m [Fig. 1(c)]. The wave conditions considered in the XBeach simulations for each storm are displayed in Fig. 2. In the

Table 2. Main numerical parameters and their values

Parameter	Value
break	Roelvink2
gamma	0.56
alpha	1.0
turb	wave_averaged
Single_dir	On
Lateral wave type	Cyclic
Lateral flow condition	Neumann
Morfac	10
Factor bed slope effect	0.15
dz_{max}	0.05
h_{switch}	0.01
dryslope	1

SWAN computations, water levels did not experience variations, and model parameters were maintained by default.

Assessed XBeach Parameters

As previously expressed, three model parameters (facua, bermslope, and wetslope) that may have a strong influence on the morphodynamics were investigated. The parameter "facua" is highly relevant in the morphological module, as it mainly governs the net cross-shore sediment transport (Elsayed and Oumeraci 2017). As XBeach only simulates short-wave energy averaged over a wavelength (wave phase is not considered), the sediment advection velocity u_a responsible for stirring the sediment and transporting it to the shore must be approximated. Van Thiel de Vries (2009) proposed an expression to indirectly calculate that velocity as a function of a wave skewness parameter (S_k), a wave asymmetry parameter (A_s), the root mean square velocity (u_{rms}), and facua following the form:

$$u_a = \text{facua}\, u_{\text{rms}}(S_k - A_s) \tag{1}$$

In shallow areas, with highly nonlinear waves, higher values for u_a are expected since the difference between S_k and A_s increases, and consequently there is larger onshore sediment transport due to the wave nonlinearity occurs.

Another parameter investigated affecting the cross-shore sediment transport was bermslope. Under the assumption that the intertidal beach slope remains relatively stable in intermediate and reflective beaches, Roelvink and Costas (2017) proposed a simple mechanism to address the challenge of simulating intertidal beach slopes in long-term simulations. Later, Roelvink et al. (2019) extended the method to two dimensions. In XBeach the sediment transport (S) is computed as

$$S = u_{\text{sed}} h c \tag{2}$$

where u_{sed} = depth-averaged sediment advection speed; h = water depth; and c = depth-average concentration:

$$S_{\text{swash}} = S - f_{\text{swash}}|S| \left(\frac{\partial z_b}{\partial_x} - \left[\frac{\partial z_b}{\partial_x} \right]_{\text{eq}} \right) \tag{3}$$

where S_{swash} = corrected transport; f_{swash} = transport factor (15); z_b = bottom elevation; x = cross-shore distance; and the last term is the equilibrium slope near the waterline. This corrected transport term is only applied in the swash region, defined by a limit where wave height is larger than water depth (Roelvink et al. 2019).

During the collision regime, dune face erosion or slumping is predominantly triggered by a combination of infragravity swash runup on the previously dry dune face and the critical wet slope. In the model, this process is considered by an avalanching mechanism triggered when the infragravity incursions reach the dune front and the dune front becomes wet. The transition of the wet and dry grid cells is controlled by a user-specified water depth ("h_{switch}"). If the critical slope between two adjacent grid wet cells is exceeded, sediment is exchanged between these cells in the amount needed in order to bring the slope back to the critical slope. As a result, sediment is brought from the dry dune into the wet profile, where it is transported further seaward by the undertow and infragravity backwash (Roelvink et al. 2009):

$$\left| \frac{\partial z_b}{\partial_x} \right| > \text{critical slope} \tag{4}$$

The maximum dune erosion rate can be limited ("$dz_{\max}$"). In this study, $dz_{\max}$ and critical dry slope used the default values, while the "h_{switch}" used the lowest limit within the recommended values (0.01), since the coarse material of the sites enhances water infiltration and soil saturation and thus reduces soil cohesion and, ultimately, dune resistance.

By varying the parameter values according to a set of combinations, a sensitivity analysis of the horizontal retreat and XBeach calibration and validation were performed (Fig. 4). Note that the default value of facua was not considered in this evaluation, since previous authors recommended higher values of facua for steep profiles (Vousdoukas et al. 2012b). The values proposed for bermslope were chosen based on values found in the literature (Roelvink et al. 2019) and the average beach face slope of Praia de Faro. For wetslope, the evaluated values covered the range of ± 0.1 around the default value (Table 3). Fig. 4 illustrates the running test sequence.

First, Storm Emma was used to assess the model sensitivity, in terms of horizontal retreat of two 1D profiles: a fully developed berm and a weak berm (Figs. 3 and 4), by applying combinations of the parameters listed in Table 3. In total, 36 simulations were performed. For each run, the erosion indicator selected was the relative horizontal displacement computed at the three elevations depicted in Fig. 3 (3 m, berm crest, and dune toe) as the relative displacement with respect to the displacement simulated by using the parameter combination with the lowest facua and wetslope, and bermslope off. This combination was chosen as a benchmark because it was expected to simulate the largest retreat. Second, two 1D cross-shore models, Profiles F4 and F6 [Fig. 1(d)], were selected to reproduce the morphological changes induced by Storm Emma in Praia de Faro (Fig. 4). The profiles were selected due to the different morphologies that they exhibited for the same exposed beach. The model was calibrated using the parameters previously studied (Table 3), and the rest of the main settings are indicated in Table 2. Third, Storm Emma was used to validate the 2D model of Praia de Faro and to compare model discrepancies between the 1D and 2D approaches (Fig. 4). Moreover, further investigations are presented to better understand the role of the gravity and infragravity wave modeling approach (2D "single_dir," 1D "single_dir," and 1D "multi_dir") in those discrepancies. Using Storm Emma as a calibration event, the model was validated for Storm Elsa (Fig. 4). For Storm Emma, the model was initiated on February 28, 2018, 00:00, and finished on March 2, 2018, 18:00 (Fig. 2). For Storm Elsa, the model started on December 18, 2019, 00:00, and finished on December 20, 2019, 18:00 (Fig. 2). Fourth, at the site of Quarteira, a 2D model calibration, using Storm Elsa, was carried out (Fig. 4); the 1D approach was not applied for this site. The parameters used for calibration are listed in Table 3 and the rest of the main settings in Table 2. After model calibration, the role played by the initial or prestorm topography was assessed by simulating Storms Elsa and Emma for both Quarteira May and Quarteira December topographies (Fig. 4). These two storms were included in the analysis to study the influence of storm energy on the model sensitivity to the input topography. In addition, the impact of Storm Emma on this site was qualitatively analyzed (Fig. 4).

Evaluation Metrics

Three typical and widely applied model skills were used: bias, RMSE, and Brier Skill Score (BSS). The bias is the difference, in meters, in central tendencies of the predicted or modeled elevation values, Z_{modeled}, and the measured elevation values, Z_{measured}, at each considered grid cell:

$$\text{Bias} = \langle (Z_{\text{modeled}} - Z_{\text{measured}}) \rangle \tag{5}$$

a positive bias means that the bed level is higher in the computed data set than in the measurements (erosion underprediction). The

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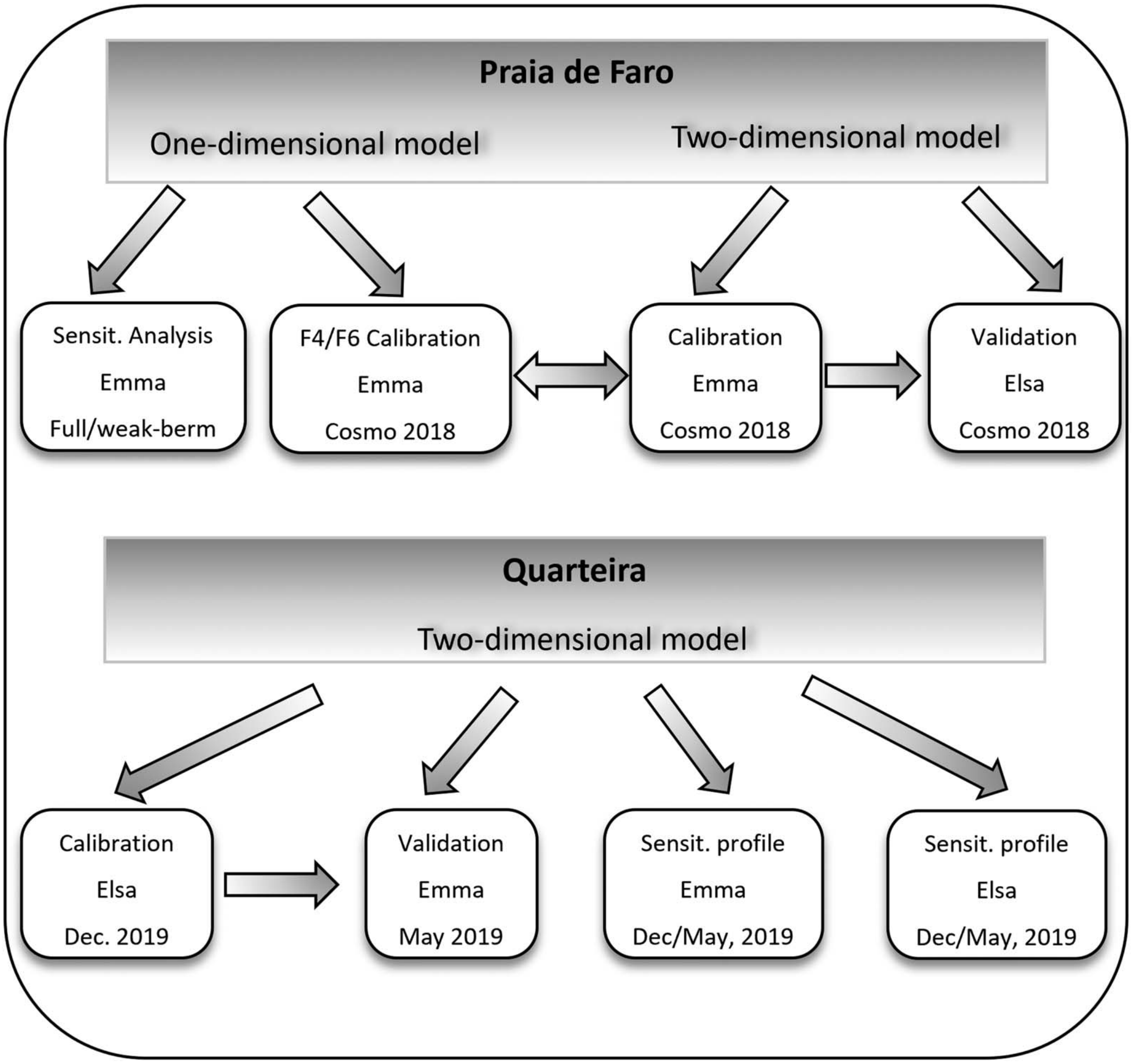

Fig. 4. Modeling exercises at Praia de Faro and Quarteira displaying the analyzed model scheme (one- or two-dimensional), the goal of the exercise, the simulated event, and the topographical dataset interpolated in the model grid. The horizontal arrows show the interactions between the runs.

angled brackets indicate the average of the readings. The RMSE is the quadratic mean, in meters, of the differences between predicted values and measured values. The RMSE is determined as

$$\mathrm{RMSE} = \sqrt{\langle (Z_{\mathrm{modeled}} - Z_{\mathrm{measured}})^2 \rangle} \tag{6}$$

The BSS provides an objective method for assessing the performance of morphological models. Conversely to the RMSE and bias skills, BSS is dependent on the profile morphology before the storm. The classification used (van Rijn et al. 2003) considers values between 0.8–1.0 as excellent, 0.6–0.8 as good, 0.3–0.6 as reasonable, 0–0.3 as poor, and below 0 as bad. The BSS can be computed as

$$\mathrm{BSS} = 1 - \frac{\langle (Z_{\mathrm{measured}} - Z_{\mathrm{modeled}})^2 \rangle}{\langle (Z_{\mathrm{measured}} - Z_{\mathrm{initial}})^2 \rangle} \tag{7}$$

where Z_{initial} = initial elevation.

Moreover, a new classification for the RMSE is proposed in this study, such that excellent represents a score lower than 0.25 m, good between 0.25 and 0.4 m, reasonable between 0.4 and 0.6 m, poor between 0.6 and 0.8 m, and bad larger than 0.8 m. This classification aims at complementing the van Rijn et al. (2003) classification. Furthermore, a coastal erosion indicator relevant for coastal risks such as the dune toe retreat (Ferreira et al. 2017) was computed to further analyze differences in model performance between the 1D and 2D schemes.

Table 3. Parameters evaluated in the sensitivity analysis and the calibration exercise

Parameter	Default	XBeach manual range	Values tested
Facua	0.1	0.0–1.0	0.15, 0.20, 0.25, 0.30
Wetslope	0.3	0.2–1.0	0.20, 0.25, 0.30, 0.40[a]
Bermslope	off	0.0–1.0	Off, 0.10, 0.12

[a]0.4 was not evaluated in the sensitivity analysis.

Result

1D Horizontal Displacement Sensitivity

The 1D sensitivity analysis performed at the full-berm profile revealed that (1) when the wetslope was set to 0.2 [Fig. 5(a)], the horizontal retreat at 3 m was sensitive to bermslope and facua. The

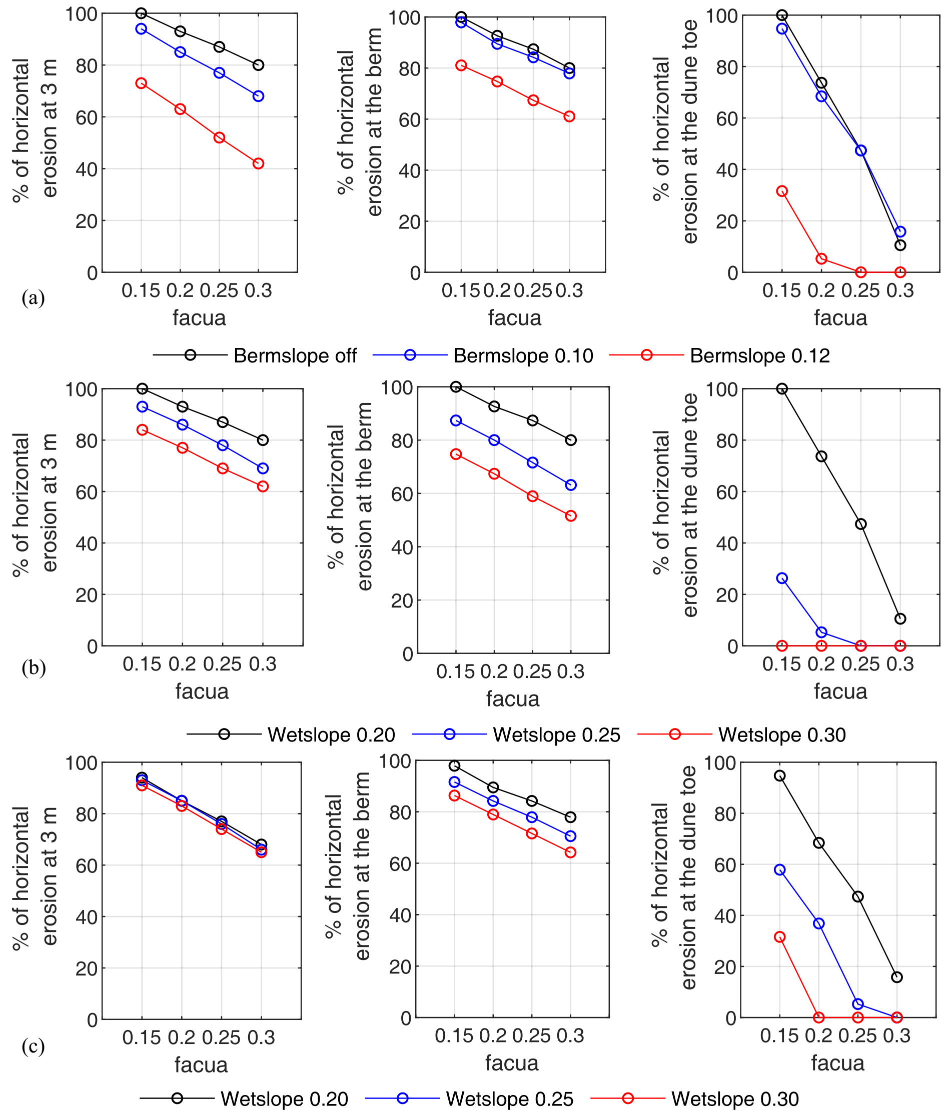

Fig. 5. Full-berm profile sensitivity results displayed as erosion percentage against the value of facua: (a) wetslope is equal to 0.20; (b) bermslope was deactivated; and (c) bermslope = 0.10.

retreat decreased linearly with increasing values of facua for all bermslope conditions. Moreover, when the bermslope was deactivated, higher erosion was computed (for the same facua) than when it was activated. Furthermore, an increase of 0.02 in bermslope resulted in more than 20% less horizontal erosion. At the berm height, facua was similarly important in controlling erosion. On the other hand, differences between bermslope off and 0.10 were minimum, but bermslope set to 0.12 reduced the retreat between 15% and 20%. At the dune toe, variations in facua still had an almost linear relationship with horizontal erosion (except for bermslope 0.12), and the erosion can be reduced by 90% when setting facua to 0.3 when compared with 0.15. The parameter bermslope was partially important; a value of 0.10 provided almost a similar effect to deactivated, but 0.12 reduced the horizontal erosion, between 70% and 100% (null horizontal displacement). (2) When bermslope was deactivated [Fig. 5(b)], a higher wetslope reduced retreat; an increase of 0.05 produced 5%–10% approximately less erosion, regardless of the value of facua. At the berm height, the influence of wetslope was higher, and increases of 0.05 decreased erosion by 12%–18%. At the dune toe, wetslope played an essential role and with facua set to 0.15, wetslope of 0.25 and 0.3 can reduce the erosion 70% and 100%, respectively, in respect to wetslope equal to 0.2. (3) When bermslope was set to 0.10 [Fig. 5(c)], the model was not sensitive to changes on the wetslope at 3 m in height. Moreover, the sensitivity to wetslope at the berm height was lower than in the case when bermslope was deactivated. At the dune toe, the model was still sensitive to wetslope. Thus, with facua set to 0.15, wetslope of 0.25 and 0.3 can reduce the erosion by 40% and 70%, respectively, in comparison with wetslope equal to 0.2.

The weak-berm profile responded to changes at the tested parameters like the full-berm profile (Fig. 6), except at the dune toe, where the model still maintained a certain sensitivity to the three parameters but was less sensitive than the full-berm profile. While all runs performed on the weak-berm profile resulted in dune toe retreat, some runs performed on the full-berm profile simulated no dune retreat (Figs. 5 and 6).

1D Calibration and Validation

A total of 36 simulations were performed for each profile at Praia de Faro (Table 3). For easier visualization of the calibration exercise, both the van Rijn et al. (2003) and the RMSE classifications were transformed into a color code, with excellent being

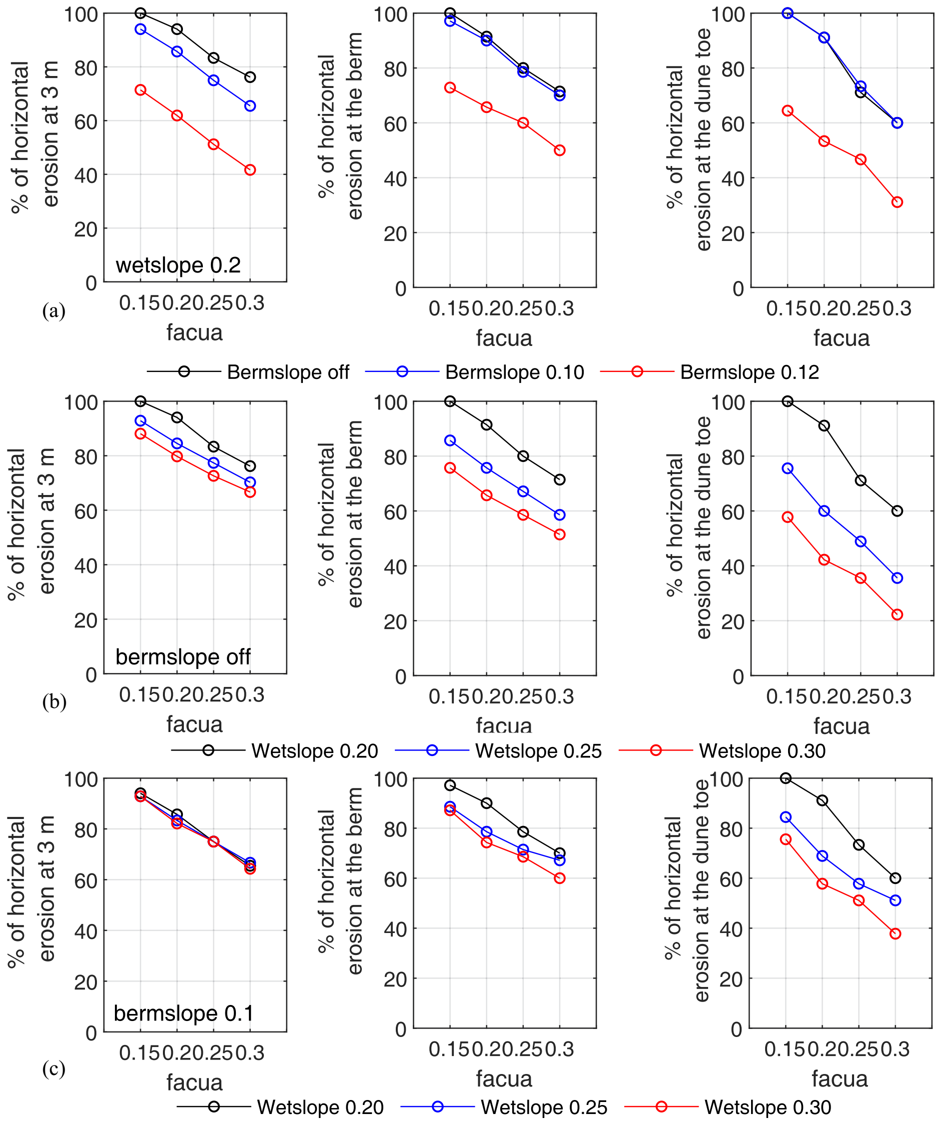

Fig. 6. Weak-berm profile sensitivity results displayed as erosion percentage against the value of facua: (a) wetslope is equal to 0.20; (b) bermslope was deactivated; and (c) bermslope = 0.10.

represented by black and bad by white (Fig. 7). The skills BSS and RMSE of the two analyzed profiles, F4 and F6, were averaged and used to compare the performance of each simulation. The characteristics of the tested profiles were reasonably different (Fig. 8). F4 was shorter, with a beach face slope of 0.12, and it was considered nonerodible after 3,732 m (cross-shore distance). F6 had a similar slope (0.11), but its backshore was wider and connected to a 6.5-m MSL height dune (Fig. 8). The calibration results revealed that when bermslope was deactivated, facua required the highest value assessed (0.3) to classify the model results as excellent (Fig. 7), regardless of the value of wetslope. As facua was reduced, the performance of the model was reduced as well. When bermslope was set to 0.10, all simulations, in general, resulted in high scores, especially simulations with facua equal to 0.20 and 0.25. Erosion was underestimated for simulations with facua equal to 0.3 and overestimated when facua was set to 0.15 (not shown here). Finally, when bermslope was set to 0.12, it was observed that decreasing facua improved the skills of the model; the best score was found with “acua set to 0.15. Therefore, several combinations of facua, bermslope, and wetslope yielded excellent data for both skills, BSS and RMSE (Fig. 7; black cells represent the best performance). Among these 36 simulations, the skills of the simulation with the highest scores for bermslope off, 0.10, and 0.12 are presented in Table 4 as Simulations 1, 2, and 3, respectively. The simulations with bermslope activated obtained slightly better skills than the simulations with bermslope off. The simulation with the lowest scores (facua = 0.15; wetslope = 0.4; bermslope = off) is represented for comparison in Fig. 8(d), highlighting the sensitivity of the model for the cases assessed in this study.

2D Simulations in Praia de Faro

Storm Emma

The model results of Simulations 1–3 listed in Table 4 were plotted against the measurements taken after Storm Emma in Figs. 8(a–c) (note that poststorm measurements after Storm Emma did not cover the dune in F6). The morphological changes simulated by the 2D model using the same values for facua, wetslope, and bermslope as the 1D model were represented as well [Figs. 8(a–c)]. The comparison between the 1D and 2D model approaches showed that the modeled erosion at the beach face was, in general, slightly higher in

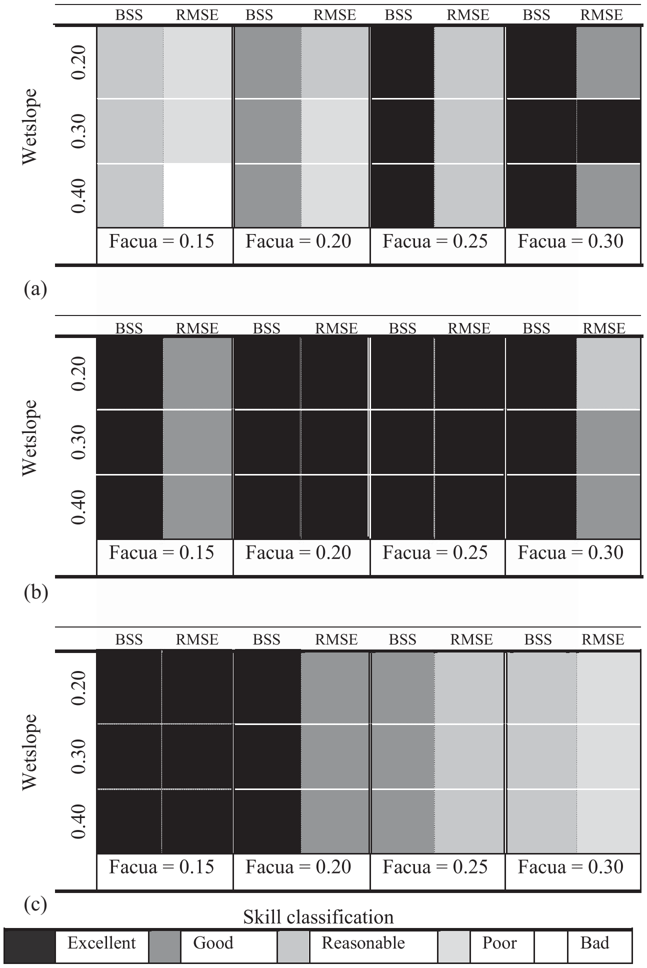

Fig. 7. Model skill classification, based on the average of the two skills BSS and RMSE: (a) bermslope deactivated; (b) bermslope = 0.10; and (c) bermslope = 0.12.

the 1D approach, especially in F4 [Figs. 8(a–c)]. However, this comparison indicated that the erosion of the dune in F6 was considerably larger in the 1D model than in the 2D model, with dune toe retreat differences up to 7 m in some runs (e.g., Table 4, Simulation 2). In general, the average BSS and RMSE (F4 and F6) for the 1D and 2D models were similar (Table 4). Among all setting combinations, and after plotting several 2D results (not shown here), the best morphological representation of the storm-induced erosion was provided by the simulation with facua = 0.15, wetslope = 0.2, and bermslope = 0.12 (Fig. 9). It does not exhibit entirely the best skills (Table 4, Simulation 5), but these settings replicated more accurately the observed dune retreat (Garzon et al. 2022) while simulating also correctly the erosion in the beach face. Furthermore, it is important to highlight two aspects: (1) when including bermslope, the erosion in all profiles was reasonably well predicted (Fig. 9), including F3, whose initial profile showed a lower sand volume (beach cusp trough) compared, for instance, with F2 (beach cusp crest). Conversely, when bermslope was deactivated, the modeled erosion was overestimated (~1 m of vertical erosion) in F3 (Fig. 9). Thus, including bermslope produced, in general, more consistent results along the five profiles; and (2) the simulation with bermslope deactivated displayed a milder slope below 0-m MSL than the one with bermslope (Fig. 9). The value of bermslope was similar to the actual beach face slopes found in the profiles F2–F6 that ranged between 0.09 and 0.12 (Fig. 9).

To further investigate discrepancies in the modeled erosion between the 1D and 2D approaches for Storm Emma, the hydrodynamic (wave height, sea level, and infragravity wave height) and morphological outputs were plotted (Fig. 10). The two models, 1D and 2D (using single-direction) simulated similar wave heights [Fig. 10(a)] and sea level [Fig. 10(c)], but the infragravity wave height computed on the 1D model was higher than on the 2D model [Fig. 10(b)]. When comparing the final profile [Fig. 10(d)], it can be concluded that dune erosion was enhanced on the 1D model with regard to the 2D. Also, the outputs of the 1D model using both the single-direction and multiple-direction options were contrasted in Fig. 10. The multiple-direction approach computed slightly lower infragravity wave heights than did the single-direction approach (but still higher than the 2D approach), as seen in Fig. 10(b), while the rest of the hydrodynamic variables were similar [Figs. 10(a–c)]. When comparing the poststorm profiles in Fig. 10(d), it was observed that the three approaches simulated similar erosion at the beach face (below 3 m below MSL) but large differences were found in the dune face. For instance, the dune retreat at 5 m above MSL obtained on the 2D model, 1D approach—multiple directions and 1D approach—single direction was 0, 3, and 6 m, respectively [Fig. 10(d)].

The spatial prediction of the seabed change for Praia de Faro is displayed in Fig. 11. Maximum vertical erosion of 2.5 m in the beach face was simulated but this erosion was not uniform alongshore as the result of the alongshore variability induced by the presence of the beach cusps (Fig. 11). In addition, Fig. 11 demonstrated the effect of the nonerodible layer to hinder the erosion in the urbanized area. Moreover, the transition between the erodible and nonerodible regions was correctly simulated (Figs. 9 and 11).

Storm Elsa

A second storm, Elsa, with lower energy, was used to validate the findings from Storm Emma in Praia de Faro. The simulation used the best setting determined in the previous section (Table 4, Simulation 5) for the 2D model. According to the van Rijn et al. (2003) classification, the performance of the model can be stated as excellent for all profiles (Fig. 12), while the bias ranged between −0.16 m (overpredicted erosion) for F1, and −0.03 m for F2. Although Storm Elsa and Emma had different energetic conditions (mid-energy and high-energy), the model was able to successfully replicate the erosion driven by both events using the same model settings.

2D Simulations in Quarteira

Storm Elsa

The calibration was carried out on the Quarteira December grid and involved the same parameters presented previously (Table 3). The modeled profiles displayed a well developed berm, especially on the eastern and central profiles of each pocket beach (Q1, Q2, Q4, and Q5) and a beach face slope between 0.08 and 0.12 (Fig. 13). Model experiments (not shown here) revealed that conversely to Praia de Faro, bermslope caused unrealistic overprediction of the erosion in the groin heads (updrift), and, hence, this parameter was deactivated for the rest of the simulations in this site. Thus, the best calibration established facua and wetslope set to 0.15 and 0.20, respectively, and bermslope off. The BSS and RMSE scores for the eastern and central profiles of each pocket beach were classified as excellent, based on the previously discussed classifications, as listed in Table 5. It is important to point out that the model reduced its ability to predict the morphology

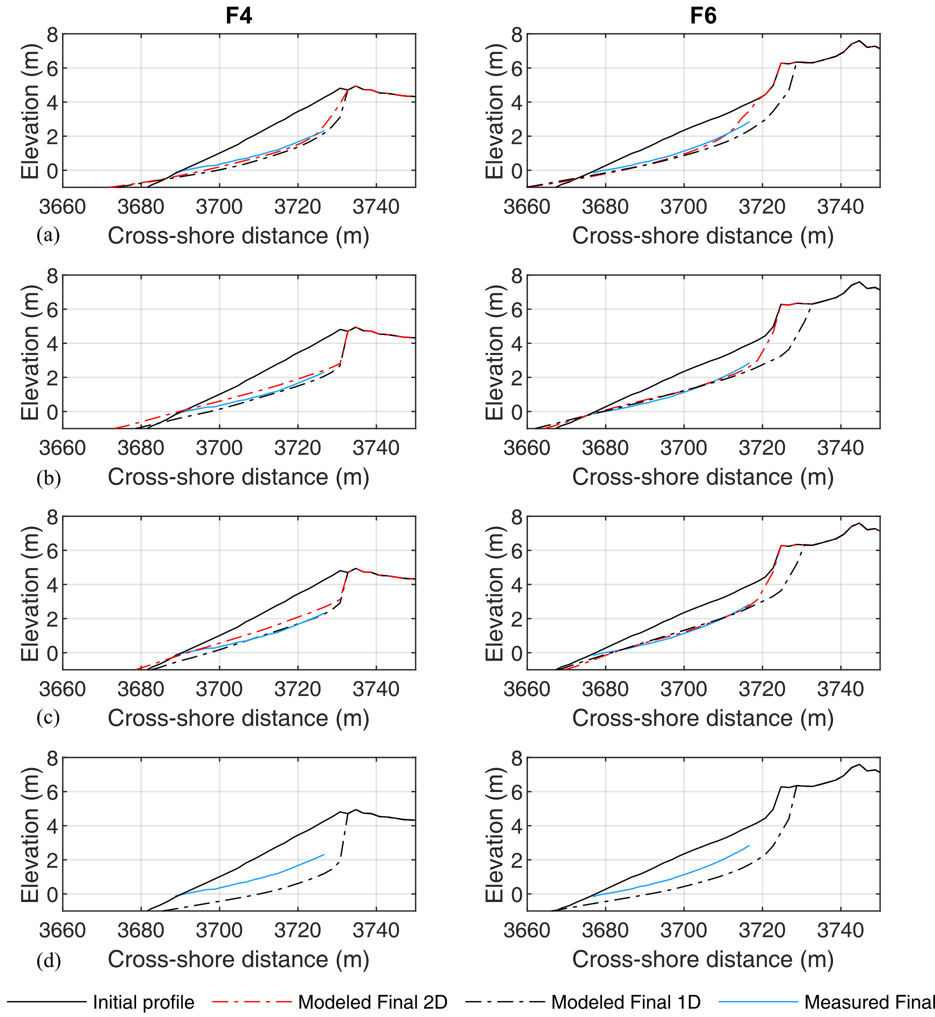

Fig. 8. Model results of the F4 and F6 profiles produced by the parametrization displayed in (a) Table 4, Simulation 1; (b) Table 4, Simulation 2; (c) Table 4, Simulation 3; and (d) the simulation with the lowest score.

Table 4. One-dimensional and 2D skill comparison calculated by averaging F4 and F6, and all profiles after Storm Emma

	Parameters			Average BSS			Average RMSE			Dune toe retreat (m) at F6	
Simulation ID	Bermslope	Facua	Wetslope	1D	2D*	2D**	1D	2D*	2D**	1D	2D
1	Off	0.30	0.30	0.95	0.96	0.86	0.24	0.21	0.31	4.3	0
2	0.10	0.20	0.40	0.97	0.97	0.95	0.20	0.18	0.23	7.3	0.4
3	0.12	0.15	0.40	0.97	0.97	0.95	0.20	0.21	0.24	5.3	0.3
4	0.10	0.20	0.20	0.95	0.94	0.94	0.24	0.26	0.28	12.0	3.3
5	0.12	0.15	0.20	0.94	0.94	0.95	0.24	0.26	0.26	9.3	2.7

Note: *averaging F4 and F6; **averaging all profiles.

of the profiles immediately downdrift of the groins (Q3, Q6, Q9; Fig. 13 and Table 5).

Sensitivity of 2D Model to Initial Topography

To evaluate the sensitivity of the model to the initial topography, Storm Emma was simulated in the Quarteira site under the two topography conditions: May and December of 2019. There were differences between the initial profiles in May and December (Fig. 14); for instance, the berm crest was notorious in the latter survey, while in May the transition from the berm to the beach face was smoother, particularly in Q1, Q2, Q4, and Q5. Moreover, in the May survey, mainly in the eastern profiles of each pocket beach (Q1, Q4, and Q7), the slope was milder and the volume of sediment above MSL was larger than in the December survey. The numerical settings were equal to those used to calibrate Storm Elsa. XBeach results for Storm Emma showed that the outputs from the two considered grids, May and December, were close (Fig. 14); for instance, the onshore limit of the eroded profile was similar for both initial conditions. Even in profiles with clearly different morphologies, such as Q1, Q4, and Q7, the final computed impact of the storm was almost equivalent.

When simulating Storm Elsa on the Quarteira May grid, XBeach was still able to fairly reproduce the erosion as well,

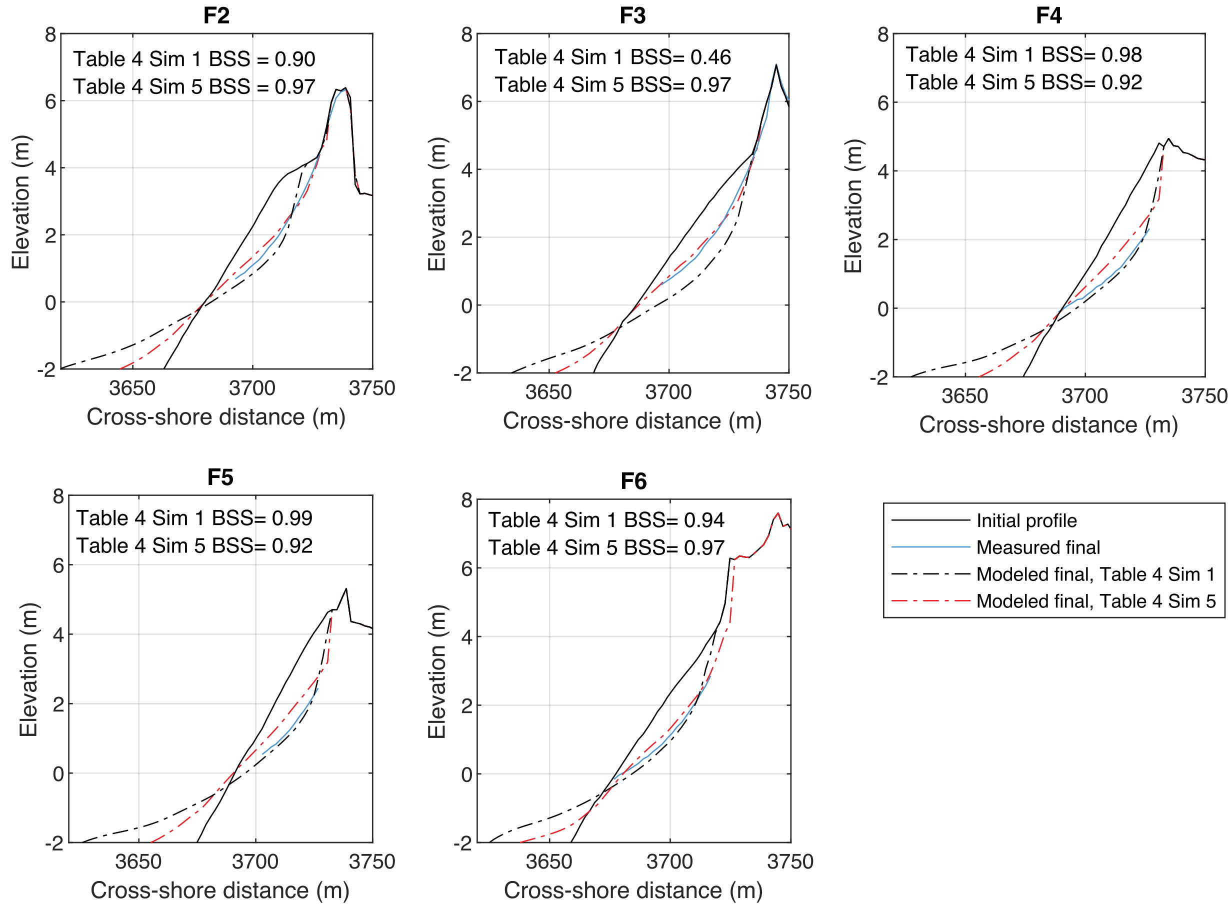

Fig. 9. Five cross-shore profiles extracted from the 2D model. The simulations correspond to Table 4, Simulation 1, and Table 4, Simulation 5 for Storm Emma.

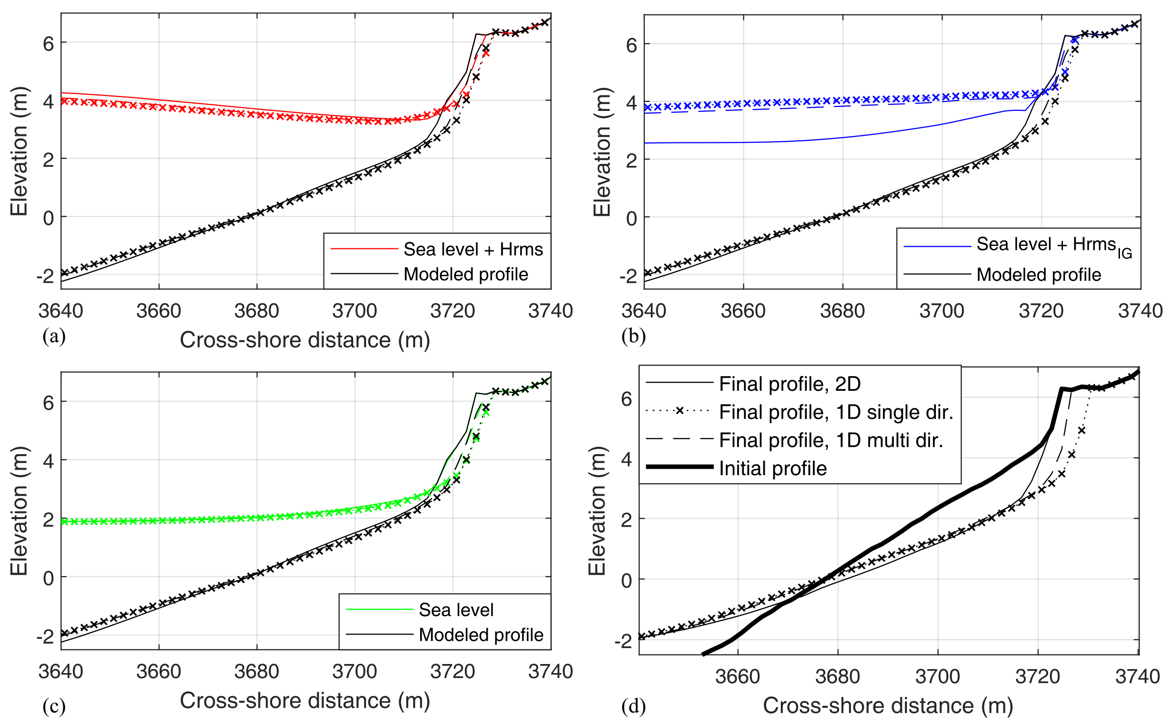

Fig. 10. (a) Sea level plus the root mean square of the wave height (Hrms) and the modeled beach profile on the peak of Storm Emma; (b) root mean square of the infragravity wave height ($Hrms_{IG}$) plus the sea level and the modeled beach profile on the peak of the storm; (c) sea level and the modeled beach profile on the peak of the storm; and (d) simulated poststorm profiles.

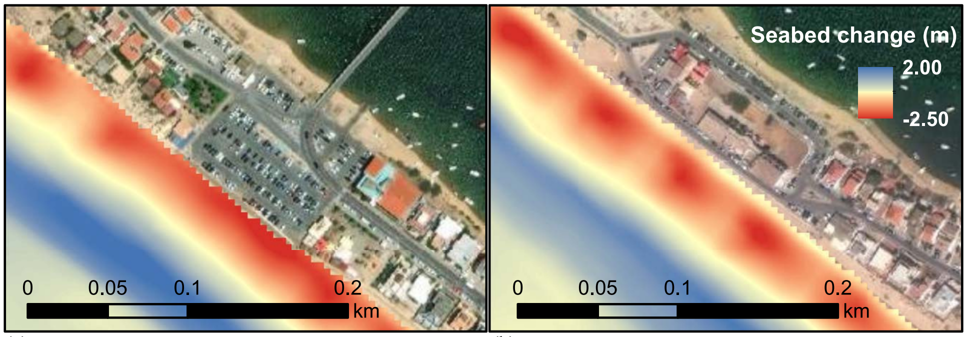

Fig. 11. Bottom elevation difference (poststorm minus prestorm) induced by Storm Emma in Praia de Faro: (a) the parking lot area (F4 and F5); and (b) the location of the F2. (The background image source is Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS USDA, USGS, AeroGRID, IGN, and the GIS User Community.)

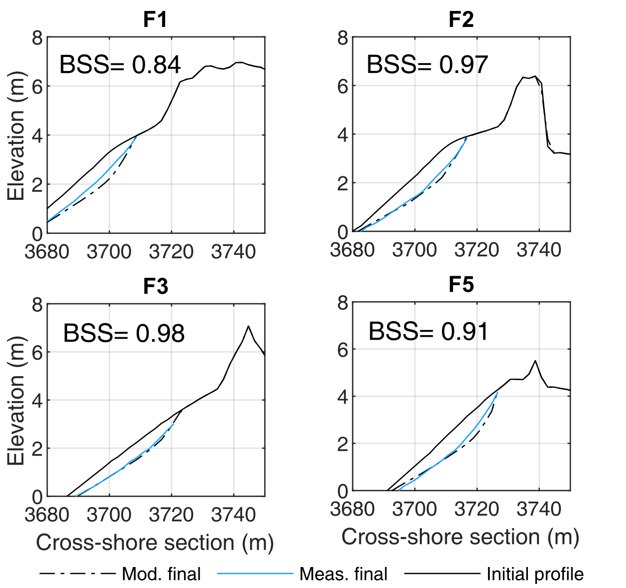

Fig. 12. Measurements against model results in four profiles of Praia de Faro for Storm Elsa.

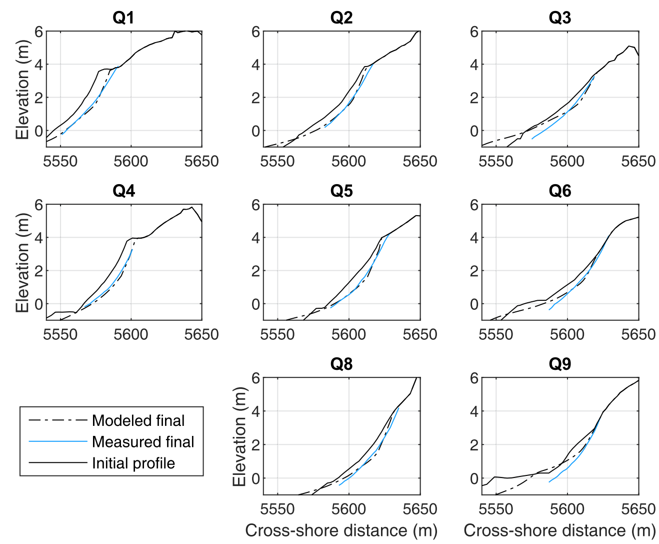

Fig. 13. Measurements against model results in eight profiles of the Quarteira December grid for Storm Elsa. The value of facua and wetslope were 0.15 and 0.20, respectively, and bermslope was deactivated.

even if the profiles were different from the actual prestorm morphology. However, the RMSE increased in almost all profiles, suggesting a lower performance. The largest differences in model performances were found in Q1, Q6, Q8, and Q9 (Table 5). In all profiles, the positive bias increased for the May grid simulation with regard to the December grid, indicating that erosion underestimation was higher on the May grid. The model ability to simulate erosion at profiles immediately downdrift of the groins (Q3, Q6, Q9) on the May grid was also low.

Storm Emma

Visual inspections after Storm Emma revealed that erosion barely reached the urbanized area at Quarteira and that morphological changes were more significant on the eastern side of each pocket beach (downdrift). It was hypothesized that the typically eastward longshore transport before the storm might have accumulated more material updrift of the groins. Thus, as observed in Fig. 14, if there was more available sediment, the erosion was higher in these regions, tending to reach a similar equilibrium profile in the area. The modeled results of Storm Emma for Quarteira showed that the groins had a clear influence on the morphodynamic of this site, and the erosion (volume and berm retreat) was more significant immediately updrift of the groins (Q1, Q4, and Q7), with a maximum vertical erosion of 2.5 m (Fig. 15). The definition of these structures as nonerodible at the model settings allowed successfully replicating the morphodynamic of this site. Thus, as it was also observed in the Praia de Faro simulations, the nonerodible layer implemented in the model behaved properly (Fig. 15). The upper section of the eastern and central beaches was not eroded, while the erosion at the western beach extended almost to the promenade (Fig. 15). It, in general, matched the field (visual) observations, confirming the positive performance of the model.

Discussion

1D Model

As has been previously highlighted (Bugajny et al. 2013; Elsayed and Oumeraci 2017; Simmons et al. 2019; Splinter and Palmsten 2012; Vousdoukas et al. 2012b), the modeled horizontal erosion was sensitive to facua. In general, a linear relationship was found between increasing this parameter and decreasing the percentage of horizontal erosion in this study (Figs. 5 and 6). Similarly, van der Lugt et al. (2019) found that changes in erosion volume scaled

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Table 5. Statistical skills for the Quarteira December and Quarteira May grids for Storm Elsa

Evaluation metrics	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9
December grid									
BSS	0.95	0.90	0.61	0.96	0.90	0.80	—	0.83	0.49
RMSE (m)	0.17	0.19	0.31	0.15	0.18	0.20	—	0.22	0.43
Bias (m)	0.03	0.09	0.15	−0.13	0.03	0.10	—	0.09	0.35
May grid									
BSS	0.90	0.91	0.69	0.97	0.95	0.65	0.93	0.76	0.34
RMSE (m)	0.40	0.22	0.41	0.21	0.17	0.38	0.19	0.46	0.61
Bias (m)	0.36	0.17	0.37	0.19	0	0.32	0.08	0.37	0.58

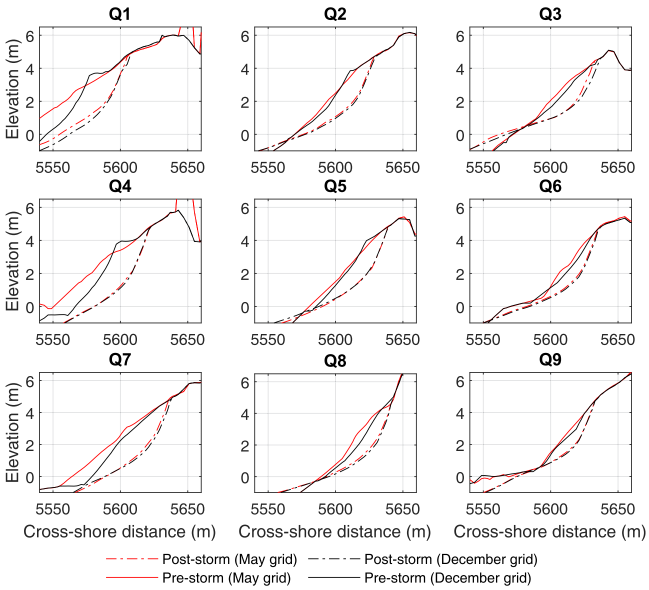

Fig. 14. Model results predicted by the 2D models of Quarteira during Storm Emma.

linearly with facua. The model seemed more sensitive to changes in facua in the dune toe for both considered profiles at Praia de Faro. One of the reasons was that the actual magnitude of the horizontal retreat at the dune toe was lower than at 3 m or at the berm crest, and therefore small changes in the model results caused large differences in terms of percentage. This also explained the bigger sensitivity found in the full-berm profile, since in this profile, the magnitude of the horizontal retreat at the dune toe was smaller than at the weak-berm profile. For instance, variations in facua from 0.15 to 0.25 (wetslope = 0.2 and bermslope = off) can lead to changes at the dune toe retreat up to 2.2 m in both profiles. Thus, simulations with wetslope equal to 0.25 caused 50% and 30% less retreat than the benchmark case for the full-berm and weak-berm profile, respectively [Figs. 5(a) and 6(a)]. The model was also sensitive to wetslope, and increasing this parameter reduced the erosion, particularly in the dune toe [Figs. 5(b and c) and 6(b and c)], as was also observed by previous studies (Armaroli et al. 2013; Cho et al. 2019; Vousdoukas et al. 2012b). This was especially observed when bermslope was off. When bermslope was set to 0.10, the model was no longer sensitive to this parameter at 3 m height and slightly sensitive at the berm height, but it was still sensitive at the dune toe [Figs. 5(c) and 6(c)]. This would partially agree with Roelvink et al. (2019), since they stated that bermslope could replace the effect of wetslope. Also, an increase in bermslope produced an enhanced onshore sediment transport and the erosion decreased with bermslope set to 0.12 [Figs. 5(a) and 6(a)] as Roelvink et al. (2019) found in their study.

The 1D calibration proved that several model combinations of facua, wetslope, and bermslope produced excellent results for the evaluation of coastal erosion at steep beaches (Fig. 7). These results also confirmed that steep profiles required larger values of facua than did the default value to compensate for the onshore transport induced by the incident-band swash processes, which are not included in XBeach (Elsayed and Oumeraci 2017; Roelvink and Costas 2017; Vousdoukas et al. 2012b). Moreover, it is important to highlight that within the limits proposed on the RMSE-based and van Rijn et al. (2003) classifications, the sensitivity to wetslope was low (Fig. 7). In the modeled profiles, the performance of XBeach was only evaluated up to 3–4 m MSL, and the dune erosion was not considered (lack of measured data), where the avalanching and slumping processes controlled by wetslope are more significant. The addition of the bermslope parameter and the reduction of facua resulted in an excellent model prediction in the tested steep profiles with different berm morphologies. Thus, when bermslope was set to 0.10 and 0.12, facua values of 0.2 and 0.15 produced excellent results. Roelvink et al. (2019) also noticed that the combination of a moderate bermslope and low facua provided good results. Similary, Lashley et al. (2019) found that only when bermslope was activated, the model was able to reproduce the steep poststorm dune profile.

2D Model

The same parameters were used to calibrate the 2D model in Praia de Faro, yielding several combinations of excellent results. As it was found in the 1D calibration, when bermslope was off and facua was set to 0.3, the model tended to provide accurate results (Table 4). However, when bermslope was included, excellent results were obtained for several combinations. This confirmed that the inclusion and use of bermslope were also adequate for a 2D XBeach model for steep beaches. Moreover, the use of bermslope reduced the variability between profiles, providing more robust results alongshore (Fig. 9). The poststorm profiles presented a relatively uniform behavior despite the existence of a prestorm alongshore variability, due to the presence of beach cusps (Vousdoukas et al. 2012a). It is important to note that the model parametrization providing the most accurate results used values that were close to the values recommended in the XBeach manual for facua and wetslope. This can avoid the model from behaving abnormally (e.g., excessive profile flattening around the waterline) as a consequence of unusual values on those model parameters, as observed in Fig. 9 and previously reported by other authors, such as Simmons et al. (2019). Furthermore, the value of bermslope chosen here was similar to the beach face slope found in the study area (Figs. 9 and 12). As the present work only focused on destructive processes induced by storms, these settings might not be appropriate to simulate constructive morphological processes in the long term, as found by Kombiadou et al. (2021).

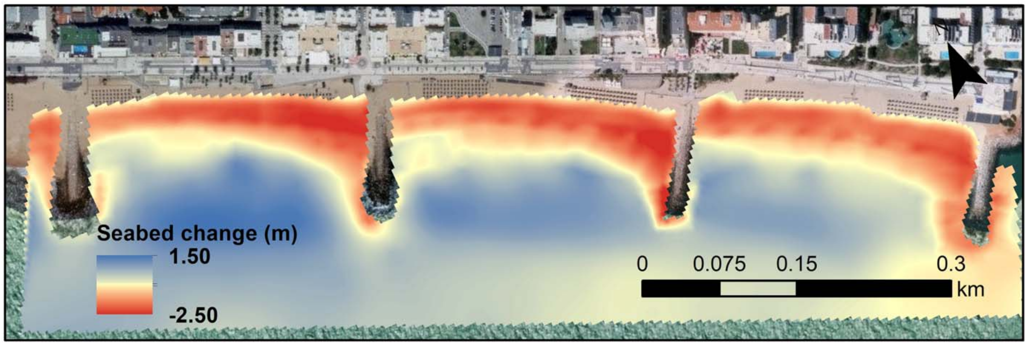

Fig. 15. Bottom elevation difference (poststorm minus prestorm) induced by Storm Emma in Quarteira using the input elevation from the survey of May 2019. The value of facua and wetslope were 0.15 and 0.20, respectively, and bermslope was deactivated. (Base map sources: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS USDA, USGS, AeroGRID, IGN, and the GIS User Community.)

The comparison between the 1D and 2D hydrodynamic and morphological outputs for the high-energy Storm Emma demonstrated that the higher erosion simulated by the 1D model was related to the higher infragravity wave height simulated in the 1D model (Fig. 10). Different model domains (1D or 2D) and different wave spreading approaches ("single_dir" and "multi_dir") resulted in discrepancies in the simulated infragravity energy, Fig. 10(b). Roelvink and Reniers (2012) declared that the swash processes in the infragravity band play an essential role in the avalanching mechanism, one of the main factors in dune erosion. Thus, the authors hypothesized that the larger energy of the infragravity band of the 1D model might lead to an enhanced erosion of the dune with respect to the 2D model, as observed in Figs. 8 and 10(d). Roelvink et al. (2018) also stated that the 1D model with "single_dir" simulated higher runup in steep beaches than a 2D model using "single_dir" as well, confirming the results depicted in Fig. 10. In fact, they compared model results against field observations and noted that the 2D model was able to predict the runup while the 1D overestimated the measurements. On the other hand, the beach face seemed similarly eroded at the end of the storm with both the 1D and 2D approaches [Figs. 8 and 10(d)].

The good performance of the model in Praia de Faro to simulate the erosion caused by the mid-energy Storm Elsa demonstrated that the results obtained in a calibration process, for one storm, can be applied to successfully validate a second storm, even with different severity. This statement agrees with Simmons et al. (2019), who found that a second storm modestly improved the calibration results, and suggested that coastal practitioners should focus more on collecting data in more locations rather than collecting data for several storms. Nevertheless, the findings of this site cannot be transferred to another site located just 10 km away (Quarteira). XBeach applied to Quarteira was also successfully validated, quantitatively and qualitatively, for Storms Emma and Elsa, but the parametrization providing good results in Praia de Faro failed in predicting the erosion in Quarteira. Conversely to the Praia de Faro model, bermslope did not provide satisfactory results in Quarteira. The model faced large problems to simulate morphological changes around the groins, and highly overestimated the erosion. When bermslope was off, it can be observed that the value of facua in this site was considerably lower than in the Praia de Faro model. It is not totally understood why the model required lower onshore transport, since the profiles also presented a steep beach face slope. Some of the reasons can be associated with the presence of the groins. Bugajny et al. (2013) carried out several 1D XBeach model simulations on unprotected, protected, and heavily protected coasts and noticed a decrease in facua with an increase in the engineering protection, reporting values of facua of 0.5, 0.3, and 0.1, respectively. Further investigations of the role of facua in protected coasts are suggested to shed some light on this process. Moreover, the good skills of the model simulating erosion under the impact of two very different storms (high-energy and mid-energy) demonstrated these calibration parameters produce adequate results for both hydrodynamic conditions.

Elevation measurements immediately before the storm in the surf zone area and the dry beach are not always available and model experiments might have to use data only collected weeks or months prior to the storm. This gap in time might lead to some errors or uncertainties when evaluating morphodynamic models. The comparison between the outputs from the Quarteira May and December grids proved that the model was largely more sensitive to input parameters than initial topography, mainly if the initial different morphologies still represented similar beach volumes, which is in line with other studies, such as Armaroli et al. (2013). This was especially evident for the high-energy storm (Emma) when compared with the mid-energy storm (Elsa).

Recommendations for XBeach Implementation on Steep Beaches

When implementing the XBeach model on an unexplored steep beach, the first efforts should be focused on collecting field data to validate and calibrate the morphodynamic model. This has special relevance in reflective beaches, since all wave processes occurring in the swash zone of these types of environments are not totally reproduced by models, namely XBeach (surfbeat). Thus, a default model parametrization could provide completely erroneous results. In the case of the lack of data for model validation and calibration, modelers working on exposed steep profiles should pay attention to facua and bermslope. In these beaches, values of facua close to the default value only perform properly when bermslope is activated, and acceptable results can be obtained by using several combinations of these two parameters. A tentative value for bermslope can be the beach face slope of the profiles. Moreover, if a dune system is present, the wetslope value must be carefully chosen but it might be close to the recommended value in the XBeach manual. On the other hand, if the reflective site presents engineering protection structures, such as groins, the impact of the wave asymmetry sediment transport is lower and, consequently, values of facua must be reduced. The use of the bermslope in these protected sites must be carefully assessed, as they might largely overestimate the erosion. Furthermore, the model would not be required to be calibrated against several storms, for both landscapes (exposed

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and groin-protected sites), which is an advantage for designing and predictive purposes.

While the 1D and 2D models simulate similar erosion in the beach face (using the same model parametrization), the erosion predicted at the upper beach and in the dune by a 1D cross-shore model was higher than the erosion computed on a 2D grid. Therefore, if the dune erosion is a major concern, different model parametrization is required in 1D and 2D models. This is especially important for the design of coastal interventions, namely if dealing with risk. Thus, at an initial phase, both approaches should be tested against observations to find the optimum parametrization for the 1D and 2D models. If the computational power is a major limitation, then multiple 1D simulations are preferable to a 2D model. Moreover, "single_dir" is more efficient than the "multi_dir" approach (Roelvink et al. 2018).

A systematic collection of elevation data can be very challenging. Thus, numerical models usually rely on a static initial topo-bathymetry, that is the elevation of the grid is not updated. In highly dynamic environments such as sandy beaches, this might result in some limitations, adding some uncertainties to the predicted morphological changes. However, even for different prestorm profile morphologies, if they maintain approximately the same amount of sand volume, the predicted erosion (poststorm shoreline and berm position) on those different morphologies is similar, mostly for highly energetic storms. This would imply that the topography of the model does not need to be periodically updated, particularly when taking into consideration the impact of storms with high energy or return period. Furthermore, steep beaches exhibit a rapid poststorm recovery response, and they are able to gain a large part of the eroded material in the order of weeks, supporting the idea that the static initial elevation approach would be sufficient to obtain reliable model results.

Conclusions

Complex morphodynamic models are suitable to assess and investigate storm impacts in coastal areas. However, these models can be sensitive to a large number of free parameters and require calibration and validation. The sensitivity and performance of XBeach have been mainly investigated in mild-slope beaches where the saturated surf zone condition is matched, while model behavior in steep beaches has received less attention. Here, numerical experiments were combined with topographical measurements collected for two large storms (16- and 5-year return period) to obtain reliable settings for better model performance in steep beaches. These experiments demonstrated that: (1) the model was sensitive to facua (parameterized wave asymmetry sediment transport component), bermslope (upslope swash zone transport term), and wetslope (critical avalanching slope) when simulating high energy storms. However, if bermslope was activated, the effect of wetslope was reduced in the beach face but still relevant in the dune face; (2) the model calibration in an exposed beach (Praia de Faro) for a high-energy storm showed that when bermslope increased, facua must be reduced, and vice versa, to properly simulate the erosion. Moreover, bermslope reduced the model results variability alongshore, minimizing the effect of upper-beach face cusps on the final model erosion; (3) with similar settings, 1D and 2D models simulated similar erosion in the beach face, but the erosion in the dune increased in the 1D simulations; (4) after calibrating with one storm, the 2D model ability to simulate erosion during two storms was classified as excellent. The value of bermslope can be related to the beach face slope and it contributed to the utilization of values of facua and wetslope close to the default values; (5) in a groin-protected site, Quarteira, the 2D model was also successfully validated, although it required different settings when compared with the exposed beach. Also, the predicted erosion in this site was not especially sensitive to initial beach topography. These findings demonstrate that these parameters produce adequate results for both hydrodynamic conditions and coastal settings. This work provides new insights on how to improve the modeling of coastal erosion processes in steep beaches and supports the implementation of morphodynamic models at exposed and groin-protected beaches.

Data Availability Statement

All data, models, or codes that support the findings of this study are available from the corresponding author upon reasonable request.

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