EFFECTIVENESS ASSESSMENT OF RISK REDUCTION MEASURES AT COASTAL AREAS USING A DECISION SUPPORT SYSTEM: FINDINGS FROM EMMA STORM

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Abstract

Storms impact coastal areas often causing damages and losses at occupied areas. On a scenario of increasing human occupation at coastal zones and under climate change conditions (including sea level rise and increasing frequency of extreme sea levels), the consequences of storms are expected to be amplified if no adaptation or further management actions are implemented. The selection of the best possible coastal management measures, considering both costs and effectiveness, will be mandatory in the future, in order to optimise resources. This work analyses the performance of risk reduction measures (beach nourishment and receptors - house and infrastructures - removal), using a decision support system comprised by a morphodynamic numerical model (XBeach) and a Bayesian network based on the source-pathway-receptor concept. The effectiveness of the risk reduction measures is then assessed by a simple index expressing the consequences to the receptors. The approach was tested at Faro Beach by evaluating its performance for a particular storm, Emma (Feb/March 2018), which fiercely impacted the southern coast of Portugal. The output results from the modelling were compared to field observations of the actual damages caused by the storm. The combined use of both measures or the solely use of the nourishment would avoid almost all observed impacts from this storm. The work is pioneer on demonstrating the use of a decision support system

for coastal regions validated against observed impacts for a high-energy storm event. The methodology and the proposed index are adaptable to any sandy coastal region and can be used to test (and improve) management options at a broad number of coastal areas worldwide, minimising implementation costs and reducing the risk to the occupation and to the people.

Keywords: storm impacts, decision support systems, risk reduction, occupation, management

1. Introduction

Storms affecting sandy coastal areas produce hazards such as erosion, overwash or flooding, which in turn promote risk to life and property damage in occupied areas. These phenomena occur on a global scale, but they have a particular acuity on coasts exposed to high-wave energy and with accentuated human occupation. Historical analysis of storm events and their consequences show that the problems associated with coastal risks are well known and object of study for many decades (see Garnier et al., 2018). The subsequent mitigation measures and management interventions vary according to the type of occupation and the coastal morphology (see Stelljes et al. 2018 for a summary of strategies, measures and results, which can be found at http://coastal-management.eu). Despite the historical knowledge of the impact of storms on coastal zones, their occurrence continues to raise problems mostly because of two aspects (Garnier et al., 2018): a "false sense of security" promoted by coastal defence works that protect occupation from small return period events, but may allow the impact of events of greater magnitude; and the loss or lack of "historical memory", corresponding to the frequent forgetfulness of previous situations. In fact, several recent examples show the negative consequences of the impact of low-frequency high-impact events on developed countries along the world: Hurricanes Katrina (2005) and Sandy (2012) in the USA (Link, 2010; Kantha, 2013; Bennington and Farmer, 2015; Clay et al., 2016), storm Xynthia (2010) in France (Bertin et al., 2012), storm Hercules (2014) in the UK (Masselink et al., 2016) or St. Agatha storm (2015) in the Adriatic (Perini et al., 2015). These events raised awareness reminding that even developed coasts and countries can be severely exposed to coastal hazards and face consequences.

Furthermore, coastal risk associated with storms is likely to increase in the future due to climate change (e.g. sea level rise and/or changes on storminess) and on-going coastal development (van Dongeren et al., 2018). Extreme sea levels (and associated coastal flooding) are expected to increase their frequency, worldwide, as a consequence of sea level rise (Vitousek et al., 2017; Vousdoukas et al., 2017), increasing the flood risk in the next decades unless timely measures are taken (Vousdoukas et al., 2018a). In the absence of further investments in coastal adaptation, the global expected annual damage is projected to increase by two to three orders of magnitude by the end of the century and the expected annual number of people exposed to coastal flooding to increase by at least one order of magnitude (Vousdoukas et al., 2018b). The latter implies critical preparation and adaptation to minimize future storm impacts (Ciavola et al., 2011a). However, most of the engineering, prevention and mitigation actions are constrained by economics and compromises must be sought between potential consequences and resources available for coastal management (Ciavola et al., 2011b). Thus, coastal authorities will need not only to implement Disaster Risk Reduction (DRR) measures but also to assess their effectiveness on risk prevention using Decision Support Systems – DSS (Ferreira et al., 2018; van Dongeren et al., 2018; van Dongeren et al., 2016; Zanuttigh et al., 2014) in order to be able to opt for the best possible solutions at an optimized cost. This requires extra efforts on the understanding and modelling of the physical forcing, coastal response and consequences towards human occupation.

Different approaches to the evaluation of the effectiveness of coastal management plans and actions can be found in several recent works, by using environmental, governance and/or socioeconomic performance indicators (e.g. Wu et al., 2017; Ye et al., 2015), analyses of questionnaires to managers or beach users (e.g. Aretano et al., 2017; López-Rodríguez and Rosado, 2017) or by assessing coastal regulation plans (e.g. Neal et al., 2018). The evaluation of the effectiveness of specific DRR measures by analysing the consequences of their implementation is, however, still limited. The existing works mostly analyse the efficiency and/or the cost-effectiveness of the DRR measures at the scale of years to decades. For example: Burcharth et al. (2014) analysed the upgrading of a typical rock armoured revetment to cope with sea level rise predictions for 2100, including a cost optimization analysis; Brown et al. (2016) and Stronkhorst et al. (2018) analysed the cost-effectiveness of different nourishment strategies from short-term (10-20 years) to long-term (up to 100 years); Huguet et al. (2018) evaluated the effectiveness of a managed realignment against existing dikes to prevent floods at La Faute-sur-Mer for 2100. Analysis of the behaviour of specific management interventions (or DRR measures) against the observed impacts of single storms are not yet commonly found in literature, being limited to few recent studies, mostly within the frame of EU funded projects (e.g. Barquet et al., 2018; Bolle et al., 2018; Ferreira et al., 2018; Jäger et al., 2018; Plomaritis et al., 2018; Villatoro et al., 2014). There is not currently in place a policy of ex-ante evaluation of the effectiveness of DRR measures against specific, high potential impact, storm events. In most cases, that evaluation is only made after the event and lessons are learned at the expenses of the observed consequences. Furthermore, only a limited number of works presented the impact of extreme storms in terms of hazards and consequences, and none of them provided (to our knowledge) a full comparison between modelled consequences and observed ones, at the field.

This work main goal is to assess the effectiveness of DRR measures against the impact (over houses and infrastructures) of a high-energy event (storm) by using a DSS based on two approaches: a) modelling the impact of a specific storm over a selected area and compare it to the performance of the DRR measures; b) using the basic storm characteristics (wave height and period, and total water level) and a pre-trained Bayesian Network (BN) to estimate the DRR performance. The link between physical drivers and human occupation is fundamental to such assessment, not only on understanding risk levels derived from drivers at a given area, but also on how a better land use and management can contribute to reduce the risk. The DSS used builds upon the works of Poelhekke et al. (2016) and Plomaritis et al. (2018). Effectiveness is here considered as the ability of a given measure to fully prevent consequences (e.g. damage to houses and infrastructures) when compared to the initial situation (comparison of storm impact before and after DRR implementation). The methods were applied to storm Emma (February/March 2018) that highly impacted the Gulf of Cadiz and Faro Beach, southern Portugal, which was selected to test the proposed approaches. The here proposed methodology for DRR effectiveness assessment can be used at any other coastal sandy area prior to the implementation of DRR measures.

2. Study Area

Faro Beach is located at Ancão Peninsula, the westernmost sector of the Ria Formosa barrier island system (Figure 1). This system, triangular in shape and with a total coastline extension of about 55 km, is extremely dynamic. Most of the observed morphological changes are related to inlet dynamics, shoreline evolution, longshore drift, overwash and storm-related processes, dune formation, backbarrier processes and artificial nourishment actions (see Ferreira et al., 2016a). Tides in the area are semi-diurnal, with average ranges of 2.8 m and 1.3 m for spring and neap tides, respectively. Maximum ranges of 3.5 m can be reached during spring equinoctial tides. Wave energy is moderate with an average annual offshore significant wave height of 1.0 m and an average peak period of 8.2 s. Dominant incident waves are from the W–SW (71% of occurrences), although E-SE conditions represent 23% of the total (Costa et al., 2001). The net littoral drift and longshore currents are typically from west to east. Storms are considered as events with significant wave heights (Hs) greater than 2.5 m (see Oliveira et al., 2018) or 3 m (see Almeida et al., 2011a, 2011b; Costa et al., 2001), with the SW ones being more energetic, and reaching a Hs of about 8.1 m for a 50 year return period (Pires, 1998). Although no statistically significant linear trends of storm characteristics were identified from the historical reanalysis record (1953 -2001) (Almeida et al., 2011b), storm variability in the area, both in terms of wave height and surge, is correlated with the North Atlantic Oscillation and the East Atlantic Pattern (Plomaritis et al., 2015).

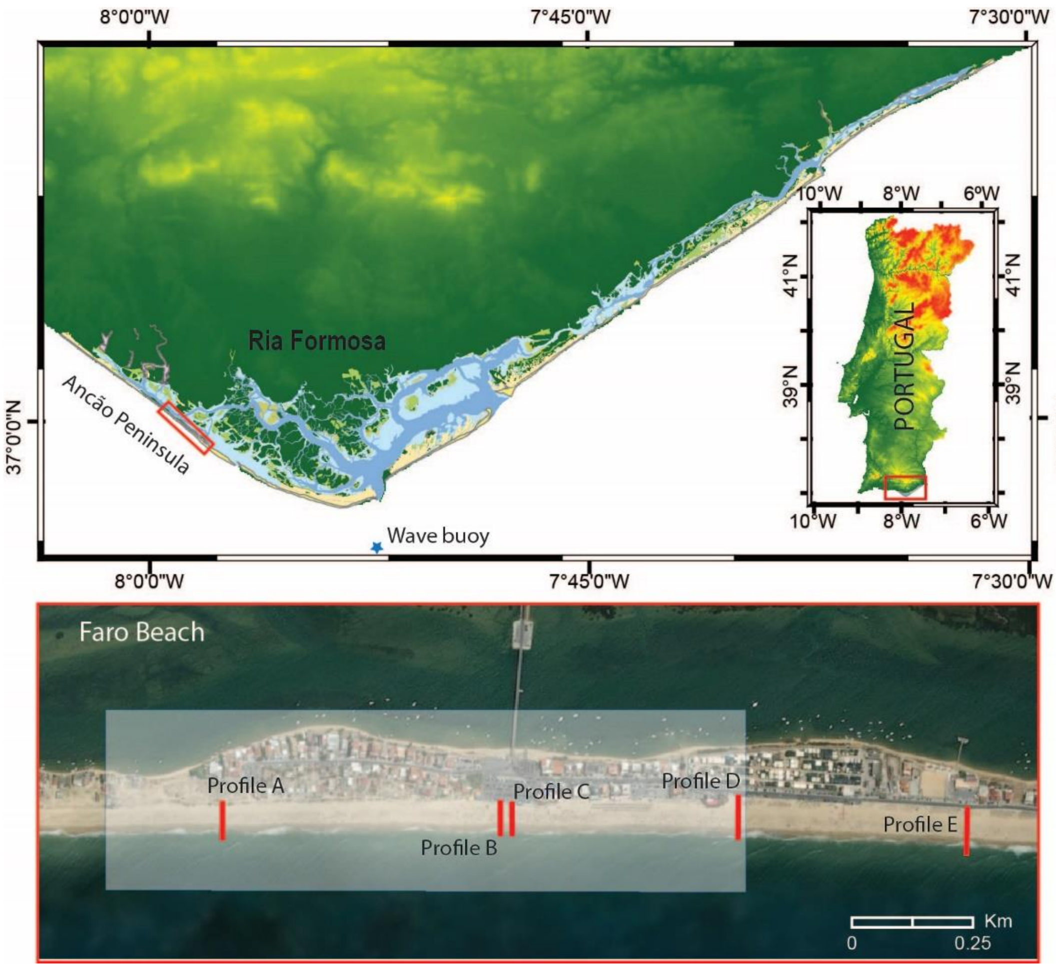

Figure 1. Location of the case study area, Faro Beach, within the Ria Formosa at the southernmost coast of Portugal. The lower panel shows an image of the urbanised Faro Beach, including the location of the pre- and post-storm measured profiles (A to E) while the shaded area highlights the nearshore area of the model domain.

Faro Beach corresponds to the occupied central portion of Ancão Peninsula (see Figure 1) and is exposed to the W–SW dominant wave conditions. Faro Beach is characterized by a steep beach-face with an average slope of around 0.1, varying from 0.06 to 0.15 (Vousdoukas et al., 2012a), that can be classified as 'reflective' following Wright and Short (1984). The oceanic beach is generally narrow, having a beach berm (occasionally a second berm can be observed) with variable width (from less than 15 m to more than 40 m). The width of the peninsula ranges from 50 m to 150 m. A large part of the dunes within the central part of Faro Beach were lowered and replaced by human occupation such as infrastructure (car parks and roads) and houses. The shoreline evolution of the Ancão Peninsula for the last decades shows a retreat at the western part (up to -0.8 m/year) and accretion to the east (Ferreira et al., 2006; Kombiadou et al., 2018) with the central part of Faro Beach showing some stability. The most relevant coastal hazards at this area have been related to the action of high-energy storms, namely erosion and overwash. In fact, the oceanfront of Faro Beach is often overwashed during spring tides and storms with long period swell waves (Almeida et al., 2012; Rodrigues et al., 2012), causing property damage. Foredune and beach erosion during storms have caused the destruction of houses and roads located at the shorefront (Almeida et al., 2012). Storms with return periods on the order of 25/50 years are expected to promote dune retreat on the order of 15/25 m, respectively (Almeida et al., 2011c; Ferreira et al., 2006). Since Faro Beach is the most urbanised and exposed area of the Ria Formosa barrier island system, it is also the one with the higher potential risk (Ferreira et al., 2016b).

Several management plans have been designed for Faro Beach (since the 1950's) but none of them implemented to this day. The most recent and detailed management plan (Plano de Pormenor da Praia de Faro) has as main goals to minimize the risk for people and goods, improve the use and the habitability conditions at the area in harmony with the surrounding environment. For that, it proposes to remove the occupation at risk and to maintain/improve the natural conditions of the ecosystem. The proposed DRR measures, similar to the ones assessed/modelled here, include the partial removal of houses at risk in combination with the nourishment of the beach and dune. The associated social and economic implications of this plan have (so far) prevented its implementation.

3. Emma storm

Emma storm (28 February to 3 March 2018) was formed SW of the Iberian Peninsula and had a track (Figure 2) similar to some of the most energetic and devastating historical storms in the area (i.e. the 1941 windstorm and Xynthia in 2010; see Garnier et al. 2018). Hindcast data in the study area provided by the Spanish Port Authority (Figure 3) show that close to Faro Beach the maximum Hs during the storm was 6.9 m, with an associated peak period of 13.3 s. The wave direction during the storm varied between 210° and 240° with an average direction of 230°. The maximum Hs corresponds to an estimated return period of about 16 years (using the values expressed at Pires, 1998). Its coincident occurrence with spring tides and the existence of a considerable storm surge (maximum values of about 0.6 m at Huelva tide gauge), contributed to a total water level of about 2.1 m above mean sea level, which corresponds to a water level return period on the order of 6-7 years, according to Carrasco et al. (2012). Due to the interdependency of storm surge and Hs in the Gulf of Cadiz (Almeida et al., 2012; Plomaritis et al., 2015), it can be assumed that the return period of the storm is mainly controlled by the wave height. However, previous research has shown that the storm impact is highly dependent on the timing of the storm in relation to the tidal stage (Plomaritis et al., 2018) and thus the occurrence of high spring tides during the storm peak (Figure 3) may have contributed to the enhancement of the storm effects.

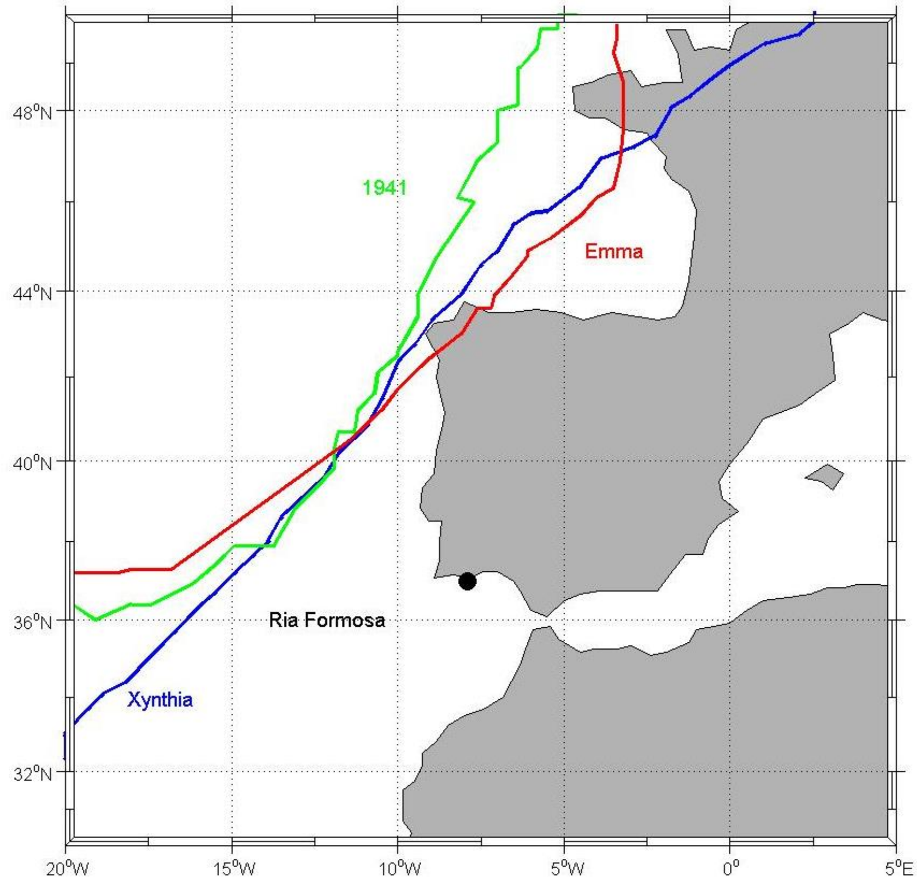

Figure 2. Storm track of Emma storm (red) and of two of the most significant previous hazardous storms in the area (1941 storm in green and Xynthia storm in blue). Emma storm track was extracted from pressure maps collected from METEOGALICIA THREDDS server. Data are a combination of forecast predictions of 24 hours window.

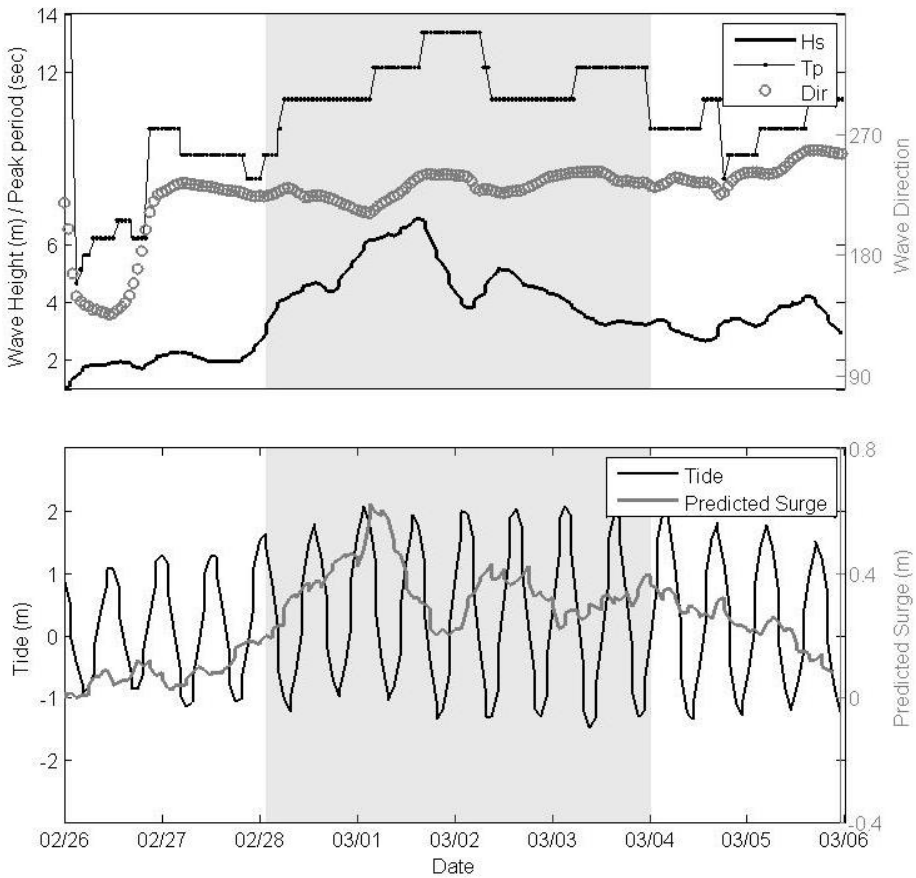

Figure 3. Hindcast prediction of wave characteristics (significant wave height, peak period and wave direction) (top panel) and water level characteristics (tide and surge at Huelva, Spain) (bottom panel) for storm Emma. Shaded area presents the simulation period, similar to the one where Hs > 3 m (storm threshold).

The Emma storm had a strong erosive effect at Faro Beach and was also responsible for overwash at specific (and lowered) areas. While overwash was responsible for piling up water and sediment over roads, at car parks and house yards, the erosive character was responsible for the damage of walls and promenades, and threatened houses placed at the front line (Figure 4).

Figure 4. Examples of Emma storm effects at Faro Beach: seafront promenade and wall destroyed behind the rip-rap seawall (upper images), overwashed roads and car parks with inland sediment transport by wind and waves (lower images).

4. Methods

4.1. Beach surveying

Five beach profiles were surveyed at Faro Beach, during low tide, using a Real Time Kinematic Global Navigation Satellite System, at 1 Hz, with a centimetre accuracy (equipment) and a decimetre precision (associated to operator errors during survey), just before (26 Feb 2018) and at the end (02 Mar 2018) of the storm. The profiles location (named A to E, from West to East) is presented on Figure 1. The eroded volumes (in m^3/m) were computed by comparing the pre and post-storm profiles and taking as lower limit 1 m MSL, since in some cases it was not possible to have data below this elevation due to the prevailing tidal (and runup) conditions. On the 3 March 2018 a post-storm survey was performed (by O. Ferreira) at the studied area to characterise the consequences of the storm, based on visual observations and notes. The areas subject to overwash and associated damages were recorded, as well as the position of the scarp/bluff line at the dune/berm and damages induced by erosion. The position of the scarp/bluff line (or the most landward observed erosion when the scarp was absent) was afterwards used to define the distance to houses and infrastructures in order to determine if those assets were within the 'potential damage' and 'damage' conditions defined by the approach (see details at the 'DSS and effectiveness assessment').

4.2. Modelling and BN approach

The hazard and impact estimations were undertaken with a combination of numerical simulations using a multi-hazard morphodynamic model, XBeach (Roelvink et al., 2009) in surf beat mode, that calculates the longwave runup, overwash and morphological changes (including erosion). XBeach is a process based model with extensive application to storm conditions. Such model has been already tested and validated for the study area (see Vousdoukas et al., 2012b) and further used within the works of Poelhekke et al. (2016) and Plomaritis et al. (2018). However, the significant computational cost of XBeach often limits its application into Early Warning Systems and Decision Support Systems (DSS). An alternative methodology, which reduces computational costs on the operational window allowing an immediate answer, is the use of a Bayesian Network approach (see Jäger et al., 2018 and Poelhekke et al., 2016). This method uses a large number of pre-computed storm scenarios to train the BN, providing a surrogate for the morphodynamic simulations in the DSS. A total of 232 different storm conditions were then run and used to train the BN. These storms were selected to represent all observed conditions and even expectable storms with higher return periods. A set of storms was chosen for the interval between 3 m < Hs < 8.1 m (~50 year return period) with the selection limits for all parameters (Hs, sea level including surge, and peak period) being available at Plomaritis et al. (2018; Table 1). In order to introduce the effect of the nourishment (as a DRR measure), all storms needed to be modeled again changing the beach morphology by including the nourishment. The data were then used to build a DSS using the BN to surrogate the modelling. The BN can be accessed in order to provide results for any incoming storm or to test the effectiveness of in place (or expected) DRR measures. This approach was based on the source-pathway-receptor concept, with the addition of consequences that were obtained from damage transfer functions. The DSS system used has been already developed for Faro Beach and the procedure followed is further detailed in Poelhekke et al. (2016) and Plomaritis et al. (2018). The boundary conditions of each storm (in this case average values during the peak of the storm for wave height, peak period and water level) are represented in the BN by separated nodes (variables) and each variable is divided in bins (e.g. wave heights and sea levels at each 1 m intervals, peak periods at each 2 s intervals). The number of bins of each variable can vary but the total range represents all possible boundary condition values. The ensemble of considered bins (i.e. for each storm condition) are also referred (or can be considered) as 'states'.

Storm Emma impacts were computed in two ways:

a) by a baseline test ("Emma modelling") using as boundary conditions the wave and surge data obtained from the hindcast model. The shaded area in Figure 1 represents the nearshore XBeach model domain. For the model validation profiles A, B and C (within the XBeach model domain) were used,
b) by applying the "Trained BN" introducing the peak storm average conditions (12 hours) as input and directly obtaining the expected impacts from the BN solution for the most similar range of conditions (set of bins or states) expressed by the BN.

It must be stated that no rigid features have been implemented at the modelling. The permeable rip-rap seawall that limits the upper beach at part of the study area (see Figure 4 upper images) was incorporated by using an increased friction at the boundary between the beach and the dune/car parking. The use of a hard layer at the model would completely avoid coastal retreat or damage behind the rip-rap seawall, which would not fully represent the effect of this coastal protection at Praia de Faro (see Figure 4, upper images).

4.3. DSS and effectiveness assessment

The DSS was applied in order to determine the potential consequences at Praia de Faro in terms of expected damage to the considered receptors (i.e. houses and infrastructures) by overwash and erosion, for a storm similar to Emma and four different scenarios:

A) Current situation (no DRR measure in place)

B) Beach nourishment including the construction of a circa 45 m wide berm (Figures 5 and 6)

C) Removal of the houses (Figure 6) placed at the ocean side of Faro Beach (between the main road and the beach)

D) Beach nourishment (B) + House removal (C)

For the current approach, 'infrastructures' include the building environment (i.e. car parks, roads, and promenades) except residential houses. The latter, together with bars, restaurants and hotels/hostels were included into the broad classification of 'houses' (see Figure 1, lower panel).

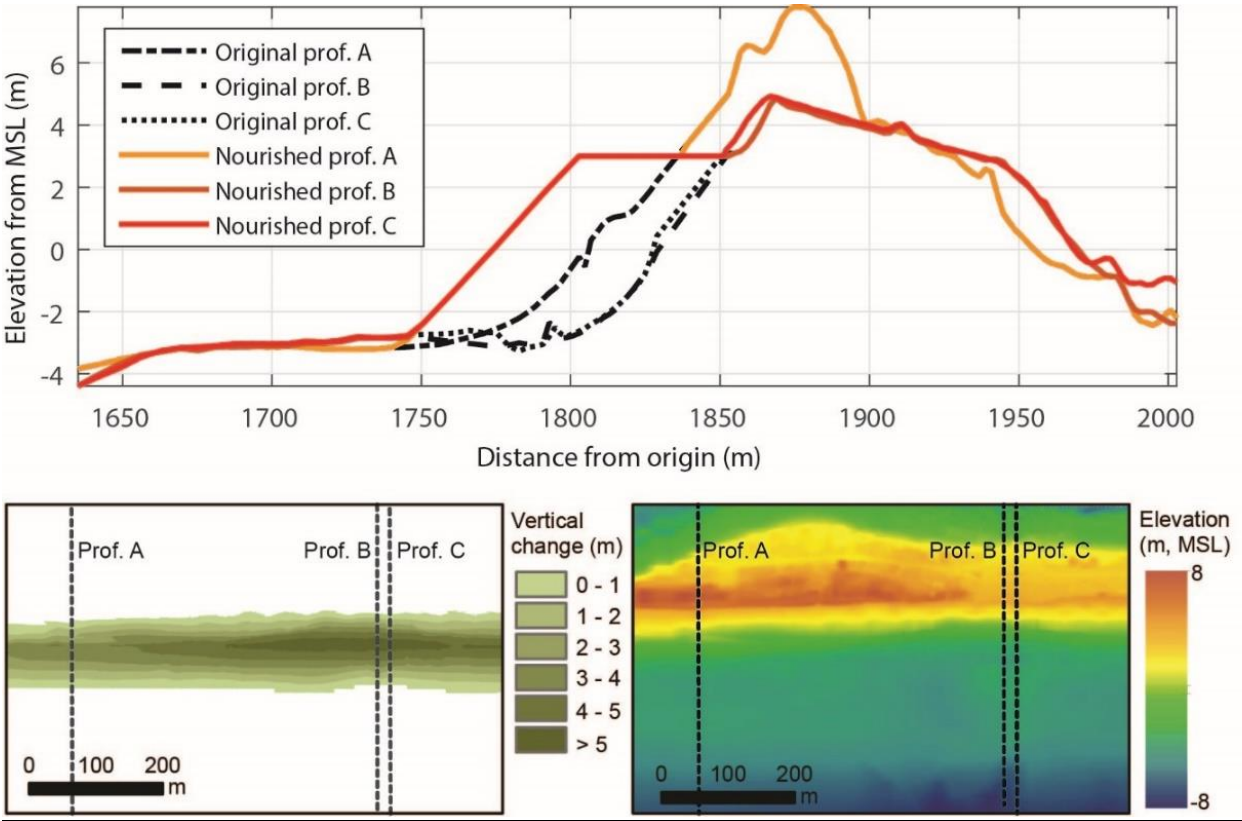

Figure 5. (a) Original (black) and nourished (color) profiles along Faro Beach; (b) Vertical elevation differences between the replenished and the original beach topo-bathymetry for the model domain; (c) Original nearshore bathymetry of the model domain. Dashed lines shows the profile´s location.

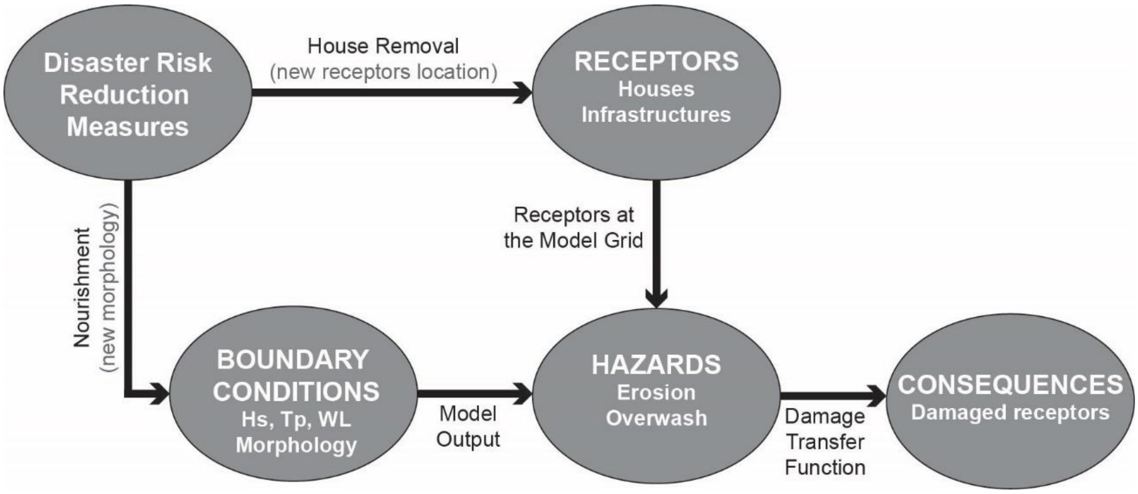

Figure 6. Design of the Decision Support System with the implementation of two Disaster Risk Reduction measures: Nourishment, changing the boundary conditions and the modelling outputs; House Removal, changing the receptors' location.

Overwash hazard was evaluated at the receptors (houses and infrastructures) using the maximum overwash discharge (Q) during the event. Specific overwash damage curves are not available for Faro Beach. Hence, a simple qualitative block damage curve was used with 2 threshold values to separate 'safe', 'potential damage' and 'damage' to receptors. For discharges smaller than 1 m^2/s the receptors are considered 'safe' while discharges equal or greater than 3 m^2/s will cause 'damage'. For intermediate values, receptors were considered as 'potentially damaged' (see Plomaritis et al. 2018 for details). Erosion hazard was evaluated for houses using the maximum erosion during an event at the house location and within two buffer zones surrounding them, one marked at 5 m radius and one at 10 m radius. The houses are considered to be 'damaged' when the vertical erosion is equal or exceeds 1.5 m at their location. The houses are considered to be 'safe' when the vertical erosion is less than 1.5 m at the 10 m buffer zone. For all other intermediate cases the houses are considered 'potentially damaged' (Plomaritis et al., 2018). For the case of erosion to infrastructures, a simpler scheme was employed where only the erosion at the actual infrastructure location was considered. For vertical erosion values equal or larger than 1.5 m an infrastructure is considered 'damaged', while for smaller vertical erosion values the infrastructure is considered 'potentially damaged'. If no erosion is observed the infrastructure is considered to be 'safe'.

The DRR effectiveness computation was performed by using an effectiveness index (*Ie*) for each DRR intervention:

$$Ie = 100\ \%\ x\ \frac{(\%\ damage\ current\ situation - \%\ damaged\ with\ DRR)}{\%\ damage\ current\ situation} \quad \text{Equation 1}$$

A zero (0%) value expresses that the DRR measure had no benefit when compared to the current situation, while 100% indicates total risk prevention by the modeled DRR. Thus, the higher the value of *Ie*, the higher the risk reduction capacity of the DRR measure, when compared to the initial situation.

The *Ie* index was applied to scenarios B, C and D (against scenario A, current situation) by considering 'potential damage' and 'damage' infrastructures identified after modelling and BN use.

5. Results

5.1. Emma storm impact and XBeach validation

Emma storm produced the total removal of the beach berm and a maximum vertical erosion higher than 2 m along the entire study area (Figure 7), exposing the rip-rap seawall and destroying some existing infrastructures (e.g. seafront promenade, walls, stairs to access the beach). The volume eroded from the upper part of the beach face (above 1 m MSL) is presented in Table 1. The measured profiles seems to pivot around mean sea level or slightly above, and thus the measured values are inferior to the total observed erosion of the upper beach profiles. It can be observed that along Faro Beach the erosion volumes were similar, ranging from 51.6 m^3/m to 60.3 m^3/m, with an average value of 56.3 m^3/m. Differences on erosion values can be attributed to the initial profiles variability, namely the presence of beach cusps. Some profiles (e.g. C and D) are also backed by a rip-rap seawall and a hard surface (car parks), which may also affect their response to a storm.

Table 1. Sediment volume (m^3/m) eroded from the upper beach (above 1 m MSL) during Emma storm.

	Profile A	Profile B	Profile C	Profile D	Profile E
Eroded volume	60.3	51.6	58.7	52.7	58.1

Overwash has been observed along the study area, mainly at car parks and at some other locations to the eastern limit of the studied area. The higher dunes at the west prevented overwash. Apart from bringing a large amount of sediment to the road and house yards, overwash also caused minor damages to a hotel, restaurants and private houses, despite the fact that several of them have been beforehand protected with sand bags.

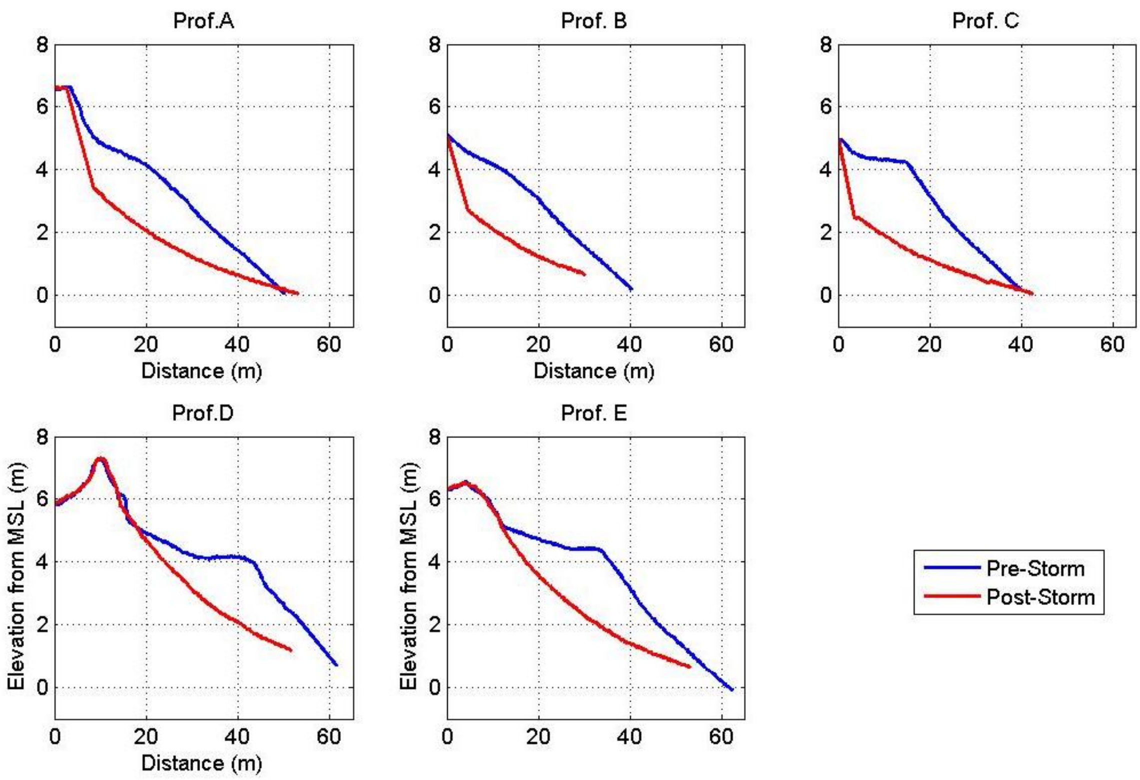

Figure 7. Measured pre- and post-storm profiles along Praia de Faro for the storm Emma. Profile locations are given in Figure1.

Using the XBeach modelling results and the measured data (post-storm profiles A to C), a validation of the XBeach model was undertaken (Figure 8). The Brier skill scores (BSS) obtained were between 0.67 and 0.9, which are considered Excellent for morphodynamic modeling simulations (Sutherland et al., 2004), reflecting a good ability of the model to simulate the morphological response. Similar to the measured profiles, the model results presented alongshore quasi-uniform erosion over the study area, which agree with visual observations during the post-storm survey. Close to the dune crest the vertical erosion values are close to 1.5 m with an absolute maximum of about 2.5 m at profile A. The model outputs show significant erosion of the dune (or the highest elevation; e.g. car parks or seafront promenade) along the central and western parts. These results were also confirmed during the post-storm visual survey.

For the given conditions, and for both the baseline and the Trained BN, the DSS estimated limited damages by erosion to the houses (5%-3%; Table 2) and infrastructures (6%; Table 3) located at the ocean western area of Faro Beach. Most of the houses and infrastructures are considered safe (64%-73% and 81%-94%, Tables 2 and 3). The remaining houses and infrastructures are classified as potentially damaged and those correspond to the occupation located at the first line of the beach front. The classification as potentially damaged house is not an indicator of actual damage but of the existence of strong vertical erosion at a horizontal distance near the houses (< 10 m). Due to the damage transfer function applied to the infrastructure erosion (no buffer zones) and the scarp like final profiles predicted by the model, no potentially damaged infrastructures were estimated. All the damaged infrastructures are located in the car parking zone. During the post-storm field survey, it was observed that no houses have been destroyed but several (27 houses and bars) have been identified within the potentially damaged condition (nearby strong vertical erosion), representing 16% of the total houses under the modelling domain. The inexistence of damaged houses and the reduced number of potentially damaged houses (when compared to the modelling and BN predictions) was most probably due to the protective action of the rip-rap seawall placed under the dune crest in front of the more severely affected area, which reduced shoreline retreat and avoided house destruction. That rip-rap seawall was only partially considered within the modelling through the use of an increased friction at its position, allowing wave impact to occur behind the structure, but probably not fully representing its protective action.

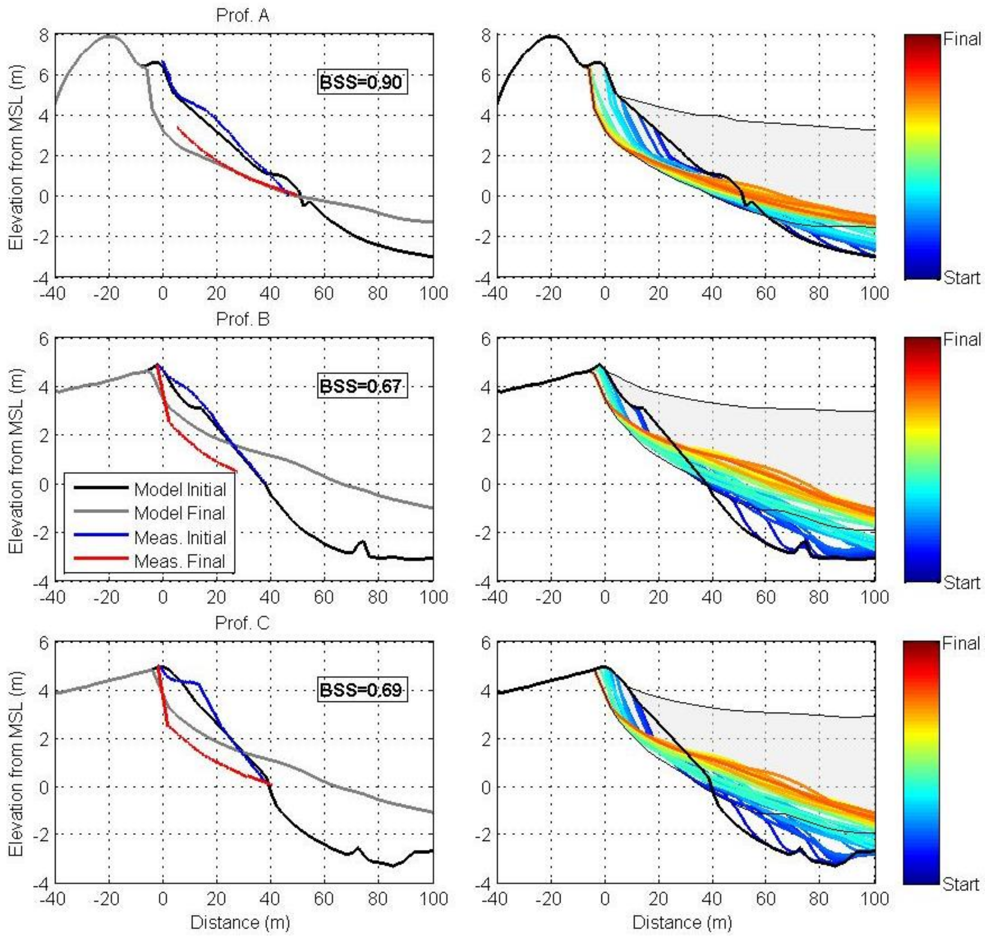

Figure 8. XBeach model validation (left panels) for profiles A to C. Profile evolution during the storm (right panels) for the same profiles. Shaded areas on the right panels represent the water envelope.

Regarding infrastructures, 3% of the total longshore model domain presented infrastructure damages, namely stairs and promenades (see Figure 4), while about 11% could be considered potentially damaged (vertical erosion at the infrastructure but without collapse). These values are in good agreement with the ones expressed by the modelling and trained BN (Table 3). The protective effect of the rip-rap seawall did not completely avoid infrastructure destruction since it is a permeable seawall and most of these structures were placed in front (seaward), above or immediately behind the rip-rap seawall and thus have been directly affected by the storm.

It is visible in Figure 8 (Profiles B and C) that limited overwash occurred at some locations, since the maximum water level exceeded the maximum profile elevation. The model predicts overwash at the central and eastern parts of the study area, which was confirmed at the post-storm field survey (see

Figure 4). Along the car parking area, the predicted mean overwash water flux was 0.22 m^2/s with maximum values of 0.7 m^2/s at the western edge of the car park. For overwash, the BN/Model estimated damages on 0% of the houses, 98%-99% of safe houses and 1%-2% (Table 4) of potentially damaged houses (overwash velocities between 1-3 m/s), while for infrastructures only the BN predicts damages or potential damages and for only 4% of the area. The field survey allowed the identification of minor damages that could be partially attributed to overwash (e.g. scour of the pavement surrounding the lamppost at the central image of Figure 4). Nevertheless, several infrastructures and houses (hotels and restaurants mainly) were directly overwashed (see Figure 4 for examples), suggesting a slight underestimation of the overwash.

Table 2. Synthesis of Safe (S), Potentially Damaged (DP) and Damaged (D) houses for Faro Beach, according to DSS, for erosion hazard, predicted by the trained BN and by the Emma storm modeling, for the 4 tested scenarios (A – current situation; B - beach nourishment; C – house removal; D = B + C).

DRR scenarios	A			B			C			D		
	S	PD	D	S	PD	D	S	PD	D	S	PD	D
Trained BN	64	31	5	100	0	0	89	11	0	100	0	0
Emma Modelling	73	24	3	97	3	0	91	9	0	100	0	0

Table 3. Synthesis of Safe (S), Potentially Damaged (DP) and Damaged (D) infrastructures for Faro Beach, according to DSS, for erosion hazard, predicted by the trained BN and by the Emma storm modeling, for the 4 tested scenarios (A – current situation; B - beach nourishment; C – infrastructure removal; D = B + C).

DRR scenarios	A			B			C			D		
	S	PD	D	S	PD	D	S	PD	D	S	PD	D
Trained BN	81	13	6	97	3	0	94	6	0	99	1	0

Emma Modelling	94	0	6	100	0	0	100	0	0	100	0	0

Table 4. Synthesis of Safe (S), Potentially Damaged (DP) and Damaged (D) houses for Faro Beach, according to DSS, for overwash hazard, predicted by the trained BN and by the Emma storm modeling, for the 4 tested scenarios (A – current situation; B - beach nourishment; C – house removal; D = B + C).

DRR scenarios	A			B			C			D		
	S	PD	D	S	PD	D	S	PD	D	S	PD	D
Trained BN	98	2	0	100	0	0	100	0	0	100	0	0
Emma Modelling	99	1	0	100	0	0	100	0	0	100	0	0

Table 5. Synthesis of Safe (S), Potentially Damaged (DP) and Damaged (D) infrastructures for Faro Beach, according to DSS, for overwash hazard, predicted by the trained BN and by the Emma storm modeling, for the 4 tested scenarios (A – current situation; B - beach nourishment; C – house removal; D = B + C).

DRR scenarios	A			B			C			D		
	S	PD	D	S	PD	D	S	PD	D	S	PD	D
Trained BN	96	4	4	100	0	0	100	0	0	100	0	0
Emma Modelling	100	0	0	100	0	0	100	0	0	100	0	0

5.2. DRR measures effectiveness

The most effective DRR measure regarding erosion promoted by Emma storm is the one that considers both nourishment and house removal, with effectiveness values on the protection of houses/infrastructures always near 100% (Table 6). The less effective DRR measure is the partial house removal alone that, according to the used prediction model, is still effective for 54% to 100% of the cases (Table 6). The beach nourishment alone presents high values of effectiveness (77% to 100%, Table 6 and Figure 9), regarding the minimization of damages (or potential damages) caused by erosion.

Regarding the damages (or potential damages) associated with the overwash all DRR are 100% effective, for all considered scenarios. The baseline test and the trained BN presented similar effectiveness results. The observed differences are mainly related to the consequences predicted for the current situation (scenario A).

Table 6. Effectiveness regarding erosion (*Ie* in %), predicted by the trained BN and by the Emma storm modeling for the tested DRR measures (B - beach nourishment; C – house removal; D = B + C). Potentially Damaged (PD) and Damaged (D) houses/infrastructures for Faro Beach.

DRR scenarios	B		C		D	
	PD	D	PD	D	PD	D
Trained BN	100/76.9	100/100	64.5/53.6	100/100	100/83.3	100/100
Emma Modelling	87.5/100	100/100	62.5/100	100/100	100/100	100/100

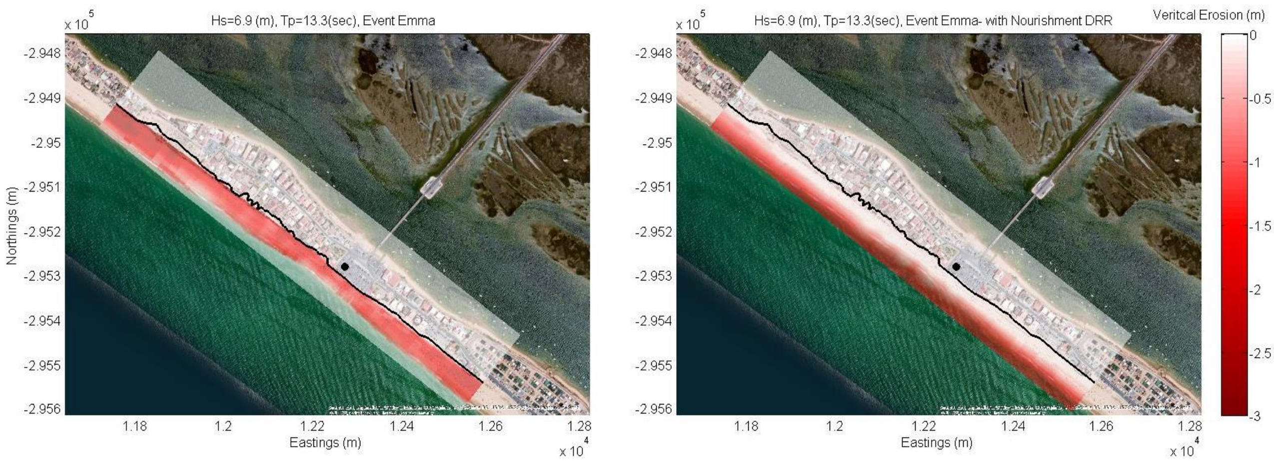

Figure 9. Example of output from the Emma modelling for vertical erosion under current morphological conditions (left image) and after beach nourishment (right image). The black line

represents the limit between the human occupation and the beach/dune. Red values landward or near that line (< 10 m) represent damage or potential damage to houses/infrastructures.

6. Discussion

Governments and managers are increasingly interested in identifying where DRR measures can be effectively used. There is, however, very little consensus as to what constitutes effective and adequate adaptation (e.g. for climate change) and how to measure it (Craft and Fisher, 2016). As for adaptation, the same occurs on the evaluation of risks and associated reduction measures, including legislation (see Drejza et al. 2011). It is therefore challenging to assess the effectiveness of DRR measures, which can be done in several different ways. Those range from the simple use of emails or interviews to ask the population about the effectiveness of coastal erosion management (e.g. Luo et al., 2015) to the quantification of the protection induced by a specific risk reduction measure (e.g. wave energy dissipation by coral reefs; Ferrario et al., 2014). Craft and Fisher (2016) stated that one metric currently used to assess effectiveness is the measurement of vulnerability and resilience. In this work we used a similar concept and determined the effectiveness of DRR measures against overwash and storm induced erosion by computing an effectiveness index directly related to the risk reduction provided by each measure. This index (and overall methodology) can be applied beforehand allowing coastal managers to test the DRR measures and to have an informed decision towards the implementation of the most effective management approach.

6.1. Modelling validation and errors

The modelling validation proved that the obtained results with XBeach are reliable for Faro Beach and Emma storm (see Figure 8). Predicted erosion and overwash by Emma modelling and trained BN, as well as the estimated damage (or potential damage) of houses and infrastructure (Tables 2 to 5, scenario A), are generically in agreement with field observations. A relatively small part of the houses/infrastructures were effectively damaged, mostly by erosion, as modelled. The predicted potential damage (mainly by erosion) of 24-31% of the houses and 13% of the infrastructures was also observed since part of the houses (16%) and infrastructures (11%) placed at the first occupation row (over the dune) was considered within the potentially damaged boundaries, during the post-storm survey. The validation performed immediately after the storm allowed to verify that the model predictions (percentages) and observation for damage or potentially damaged houses/infrastructures differed mostly in less than 10%, reaching a maximum of 15% (at the potentially damaged houses). This can be regarded as an overall measure of the model uncertainty and several factors might contribute to it. One such factor is that the BN, and consequently the DSS, always starts from the same initial bathymetry/topography or from a limited selection of initial bathymetries, and thus differences between the measured and the initial model profiles can exist. This is a limitation (from an assumption) of the current methodology that can be solved in the future by integrating different topo-bathymetric conditions at the modelling. It can be seen in Figure 8 that differences between initial modelled and measured profiles are relatively small and mainly due to alongshore cusps that can be frequently observed in the area. In the present case, volume differences between the initial profiles varied between 8 and 16 m^3/m, which represents a change of 14-28% of the average eroded volume, and thus that can be assumed as the average error associated to the variability between measured and modelled initial profiles. A potential improvement of the method will be to consider different possible initial morphologies and analyse the potential storm consequences under a range of morphologies.

Differences between the final model and the measured profiles could also be due to the presence of a protection work (permeable rip-rap seawall) that is present in the area but has been just partially introduced in the model. Profiles B and C are backed by the car parking area of Praia de Faro and by the seafront promenade, which are protected by large boulders (rip-rap seawall) buried in the sand. During the present event a large portion of the seafront promenade was undermined and destroyed by the storm (see Figure 4), however, this behaviour is not fully captured by the post-storm profiles (due to difficulties on surveying over the boulders). Similarly, part of the eroded area in Profile A presents contrasting geotechnical properties relatively to a dune as it is composed by a more compacted sediment layer with a large content of clays. That may explain the greater dune retreat simulated by the model compared to the observations. In addition, the boulders and resistant soils increased the wave reflection, which can in turn increase the offshore transport of sand and further lower the beach profiles. This might be responsible for the higher expressed vertical erosion at the measured profiles when compared to the modelled ones.

The slight underestimation of the overwash (when qualitatively compared to the observed overwash and consequences) can result from the non-inclusion of short wave induced overwash (only infragavity wave overwash is predicted by the model) and also because the resolution of the surge model may not be enough to fully capture the surge magnitude and, consequently, the total water level. The absence of a local tidal gauge does not permit a more thorough validation of the model.

Finally, a source of inaccuracy on the model prediction is the wave and surge prediction models resolution. The overall final result from the morphodynamic model highly depends on the input values (from the predictions) and thus improved (and validated) regional wave and surge models are highly important for the achievement of good and representative results. A validated model train that would better downscale the regional prediction could result in an even more accurate representation of the storm consequences. Nevertheless, as already stated, the observed uncertainty of expected damages was relatively small, with differences between modelled and field observations being always below 15% of the total maximum potential damage and in most cases between 5 and 10%, which can be considered a good performance of the model for such a high energy event as the Emma storm.

6.2. DRR effectiveness

The modelling results can be used to further train the BN and to improve the results of the DSS. However, since the BN is a surrogate of the modelling and uses bins that represent similar storm conditions and morphologies, a storm at the BN is not represented by its exact values and respective modelling but by the overall modelled erosive conditions (and impacts) associated to the bins (e.g. Hs, Tp, sea level) within which that storm fits (Jäger et al., 2018; Poelhekke et al., 2016). Thus, damage and potentially damage values for overwash and erosion must be seen as representative values for storms with similar characteristics and will incorporate a certain level of variance. However, given the fact that the storm characteristics are probably a result of an operational forecast model with associated prediction errors, the BN approach in a DSS provides a more robust prediction since it informs about the intensity of the hazards and associated damages based on a number of similar storms. Similarly, the effectiveness of the DRRs is calculated based on the same principles.

All modelled DRR have a total effectiveness (100%; Tables 4 and 5) in reducing overwash impacts since the level of modelled (and field observed) overwash was not extreme at this storm. The most effective DRR measure to reduce the damages associated to erosion is the combination of nourishment and house removal, followed by the nourishment alone (Table 6). For this storm (circa 16 year return period) these two measures have almost the same effectiveness level. This is however probably not valid for storms with higher return period where the nourished berm can be fully eroded.

The trained BN predicts always more damages than the single Emma storm modelling, however both tests provide similar tendencies with increased erosion hazards and consequences in comparison to overwash. This results from the inclusion of several tested storms under the generic conditions that represent the Emma storm within the BN. This makes it a stricter tool for calculating potential damages and effectiveness of DRR measures. The BN outcome has, however, some level of uncertainty since each storm is then represented by a set of bins (or stages) with some variability. For instance, at the used BN (see Plomaritis et al., 2018) the wave height bins have intervals of 1 m, with the Emma storm being represented by wave heights ranging from 6 m to 7 m. That can be minimised by increasing the training of the BN for each state or by detailing the discretization intervals (e.g. each half meter), which (for both cases) requires a higher number of modelling simulations.

The obtained DRR effectiveness for the nourishment (and nourishment + house removal) considers that the beach morphology is always equal to the one immediately after the nourishment intervention, representing a maximum protective effect. This effect diminishes with time since there will be sand removal by longshore transport on an average of about 100,000 m^3/year (Santos et al., 2017). Thus, the presented DRR effectiveness assessment considers that the nourishment is maintained over time. It would be also possible (not presented at this work) to estimate the beach nourishment reduction with time and to simulate the decrease in effectiveness in order to provide the coastal manager with a clear indication of when a new intervention should be performed.

Regarding partial house removal, the DRR effectiveness assessment considers that there is no dune recovery with time (natural or human incremented). Thus, although probably correct for the moment immediately after the DRR intervention, the effectiveness of the measure will probably increase as dunes naturally grow with time. Natural dune recovery after house removal has been observed at the area (after interventions in 1987 and 2015) and it is expected to occur if this measure is further implemented.

6.3. The DSS in coastal management

The results expressed along this work prove that it is possible to determine and compare the effectiveness of different coastal management actions regarding their potential to minimise coastal risks. The tested management actions are not restricted to the reduction of the hazard by minimising the impact of the storms at the pathway (e.g. beach and dune nourishment) but also include the reduction of risk by changing the receptors (e.g. new land use or improved management), allowing the test of multi-disciplinary approaches. That can be done ex-ante, for specific storms (as here represented) or for a large set of pre-defined conditions. The complex and time-expensive modelling can be integrated into a BN that can be retaken, when needed, to reassess the effectiveness of a new defined condition. This decision support system can be adapted to any sandy coastal area and afterwards implemented. It can also be used for a vast set of potential measures, including the ones here tested (house removal and beach nourishment) but also dune recovery, detached breakwaters, placement of submerged bars, etc. By using the here proposed effectiveness method and index, the managers can have a clear idea of the effects of each measure beforehand and evaluate the cost-benefit. Thus, they have the possibility of taking an informed option towards the improvement of coastal management actions at their region. It will allow to reduce budgets and optimise costs, since an approach of trial and error can be made a priori, avoiding (or minimizing) the costs of implementation of a given measure. For instance, several nourishment designs can be tested in order to define the one that minimizes the risk to a desired level (using the effectiveness index) at a lower cost. It also allows, on natural systems, to better define set-back lines for storm effects associated to a pre-established return period.

A full cost-benefit analysis of coastal management alternatives is desirable and could be performed jointly with the proposed approach. By including such analysis, it is possible to simulate the benefits for the economy of a coastal area and, as well, the benefits for the ecosystem services provided by the coastal zone, thus contributing to a better assessment of the impact of the management actions.

7. Conclusions

This work proposes the use of a validated numerical model or of a surrogate trained Bayesian network to determine the potential impacts of storms at coastal areas, with and without disaster risk reduction measures, and to further evaluate the success of such measures. It also presents a new effectiveness index to evaluate, in a simple and comparative way, the effect of the measures. The model, the Bayesian network and the effectiveness index were tested at Faro Beach, for Emma storm, a 16 year return period storm that caused infrastructure damage and threatened the occupation (houses, bars and hotels) mostly due to erosion but also (to a minor extent) by overwash. The results proved that the use of beach nourishment (environmental based solution) alone or jointly with partial house removal (societal based solution) would reduce the impacts of the tested storm to a residual level. This approach represents, to our knowledge, the first attempt to demonstrate the effectiveness of a coastal DSS against a specific and well-documented high-energy storm. The methodology is given as example for further application in the future at global level, in order to better identify and test coastal management measures that are effective in reducing risk to coastal populations. As demonstrated, the methodology includes physical drivers (waves, sea level) and human occupation and allows testing both environmental and societal based coastal management actions, jointly or separately. Such approach will also help to optimise resources, which is in turn a factor of paramount relevance taking into consideration the potential increase of coastal risks due to climate change (i.e. sea level rise and increased frequency of extreme sea levels) and the increment of human occupation at coastal areas.

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