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Wave-induced flooding risk assessment for the Development of Early Warning Systems.

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Abstract

Communities can be vulnerable to wave-induced flooding and the risk is expected to increase with rising sea levels and population growth. Under this threat, early warning systems are relevant instruments for effective risk reduction strategies. These systems combine accurate hazard estimations with risk level classification for specific coastal receptors such as pedestrians. Regarding hazard computations, numerical models are gaining in popularity among the possible tools due to their robustness in simulating wave nearshore processes. Regarding risk level classification, the determination of the limits that trigger those levels requires a detailed evaluation. In this study, SWAN+XBeach (non-hydrostatic mode) is used to simulate wave overtopping at two sites of the Portuguese coast, Praia de Faro and Quarteira, during three storms with varying severity. Two overtopping indicators are simulated to represent coastal flooding: mean overtopping discharge and maximum depth velocity. Field observations of impacts caused by these storms are categorized into four risk levels for pedestrians (no risk, low risk, moderate risk, and high risk). Then, the modelled indicators are used to estimate equivalent risk levels based on limits proposed in previous risk assessment sources such as Coastal Engineering Manual 2002, Eurotop (2018), HIDRALERTA, FLOODsite (2009). The comparison of the observed and estimated risk levels reveals that all sources can identify the high risk and the no risk level episodes. However, some discrepancies between sources are found to estimate moderate risk episodes. This study demonstrates that the proposed methodology is appropriate to simulate wave overtopping and properly characterize risk levels for pedestrians.

Keywords: Wave overtopping; Risk assessment; Forecast and alert system; XBeach; Portugal.

1. INTRODUCTION

Many low elevation coastal areas are highly vulnerable to wave overtopping and coastal flooding driven by extreme oceanic events. Moreover, the impact of these events on coastal populations will be largely exacerbated by climate change. To address these challenges, managers consider the implementation of early warning systems to enhance resilience in exposed communities. These systems are preventive measures that help communities to be prepared for hazardous climate-related events (e.g. coastal storms). The development of hazards forecasting systems in exposed coastal areas is a very efficient tool that can help to minimize the loss of lives, livelihoods and assets, and anticipate the effects of climate change. However, the development of early warning systems to provide estimates of overtopping hazard information still faces many obstacles, such as the lack of both field overtopping measurements and efficient tools to compute the hazards, and the significant variability between sources (and receptors) to establish critical values to assess overtopping hazards. Among the existing tools, process-based numerical models are gaining in popularity against other approaches such as empirical and neuronal network methods due to their robustness and versatility to deal with different coastal landscapes and hydrodynamic conditions. This study aims at contributing to the development of more reliable wave-induced flooding forecasting systems by combining numeric modelling, hazard level classifications reported in the literature, and damage information collected in two vulnerable sites.

2. METHODS

In this section, the study areas are introduced and their main characteristics are described. Then, storm impacts collected at both sites are presented. Also, a detailed explanation of the process-based numerical model framework designed to compute the wave overtopping indicators is carried out. Later, several sources found in the literature that characterize the risk based on the severity of wave overtopping indicators are presented. Finally, the comparison between observed risks and the risk levels estimated is assessed.

2.1 Study sites

Two sandy beaches located on the southern coast of Portugal, Praia de Faro and Quarteira, were selected for this study. Praia de Faro is an open beach located in the Peninsula of Ancão, a narrow barrier that separates the Atlantic Ocean from an interior coastal lagoon (Figure 1). The beach can be classified as reflective with an average slope of around 0.10 (calm conditions). The area investigated in this study is located in front of the parking lot, where a walking wooden path separates the beach face from the urbanized area (Figure 1 and Figure 2). This path is located at 4.6 m above mean sea level MSL and the beach width is approximately 40 m. These features make this site highly vulnerable to wave overtopping (Almeida et al. 2012). The other site included in this study, Quarteira, is located ten kilometers NW from Praia de Faro (Figure 1). This is an urban beach with rocky groins. In the back, the beach is limited by a promenade with an elevation of 5.5 m. This site can be also classified as reflective with an average beach slope of 0.10 and a beach width of more than 60 m.

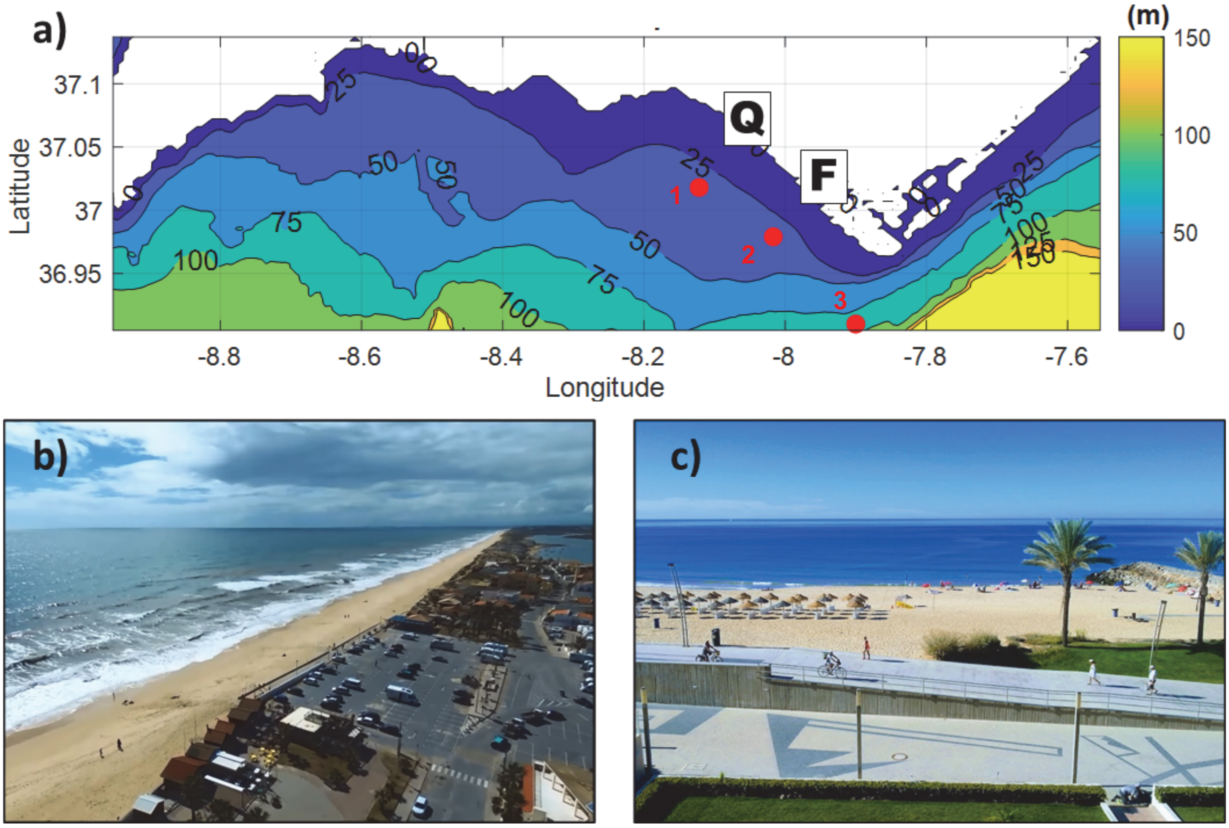


Figure 1. a) Bathymetric contour lines of the southern coast of Portugal corresponding to the SWAN model domain. The locations of both study sites are marked with “F”, Praia de Faro, and “Q”, Quarteira. The red dots 1 and 2 in front of the study sites display the location of the XBeach offshore boundary, while dot 3 represents the location of the Faro buoy. b) Parking lot at Praia de Faro and c) the urban beach at Quarteira where the risk levels are assessed. Source: Google.

2.2 Storm events

On the 24th of April, 2021, storm Lola was felt in the Continental Portuguese region. Located at the southwest side of the Iberian Peninsula, its winds generated waves that travelled up to the Gulf of Cadiz and reached the southern Atlantic coast of Portugal and Spain. At the location of the Faro buoy, the significant wave height Hs was higher than 3 m, the peak period was 14.66 s and total water levels ranged between 0.51 and 1.20 m above MSL, according to Puertos del Estado forecast system. Overtopping episodes at Praia de Faro were reported from 12:00 until 14:00 (Figure 2).

Two storms with different levels of severity were selected to test the methodology in Quarteira. Storm Emma was an extreme event that hit the southern coast of Portugal in March of 2018 (Ferreira et al. 2019). The Hs observed at the Faro buoy was more than 6 m, with a peak period of 12 s (during the high tide) and total water levels of 1.88 m above MSL. Local authorities reported that the seawater reached locations at least 100 m hinterland. Storm Elsa on 20th of December, 2019, a 5-yr return period storm, was less energetic and the maximum Hs was 5.15 m and 11 s peak period coinciding with neap tides (maximum water level 1.0 m approx. above MSL). Visual inspections indicated that the maximum runup did not exceed the elevation of the promenade.

Figure 2. Three photographs taken by the authors in Praia de Faro on the 24th of April, 2021 at 12:23 (left side), 13:20 (middle) and 13:36 (right side).

2.3 Numerical modelling framework

To model wave overtopping, a numerical framework was used consisting of SWAN + XBeach. The SWAN model covered the entire southern Portuguese coast (Figure 1) and it had a structured grid with an approximated resolution of 350 m and 600 m in the cross-shore and alongshore directions respectively. This model was used to propagate and downscale the wave conditions from the Faro buoy (~ 100m depth) to 25-30 m depth, where the XBeach, non-hydrostatic mode (Roelvink et al. 2009) offshore boundaries were located (Figure 1). Then, a 1D XBeach model was used to propagate the wave conditions to the shore and compute mean wave overtopping discharges and maximum depth velocities (overtopping indicators) at the target locations. Morphological processes were not included in this mode.

In the Quarteira model, grid resolution varied between 2 m (offshore) and 0.5 m (nearshore and emerging areas). The profile length was 5700 m and the offshore boundary was located at 25 m water depth. The flow boundary conditions were set to nonh_1d in the front and abs_1d in the back. Neumann conditions were selected for the lateral boundaries. A manning coefficient of 0.02 s $m^{-1/3}$ was chosen to represent the bottom roughness. The groundwater flow module was also considered and the hydraulic conductivity or Darcy k was 0.0004 m/s. A two-layer model was applied (nonhq3d on) to better simulate the dispersion relation and shoaling of waves in intermediate depth. The layer distribution was set to the default value (0.33). The parameter maxbrsteep controlling the maximum wave steepness criterium was set to 0.5. Jonswap spectra were selected to represent the wave energy spectra with the default value for the peak enhancement factor (3.3). The CFL was set to 0.55. Discharge values were output at the interest location (seaside edge of the promenade) every half second. The simulation time varied between runs but all of them included the same number of waves, 600. After a warm-up period, the up-crossing method was selected to calculate the mean period that multiplied by 600 waves resulted in the time used to compute both indicators. Each simulation was performed five times using identical oceanographic conditions to better account for the stochasticity effects of the wave overtopping process.

The input topography of the non-hydrostatic simulations was measured after storm Elsa, representing a post-storm morphology. The elevation of the urbanized area was obtained from a UAV survey conducted in May 2019. Regarding the input bathymetry, two datasets were included: APA (Agência Portuguesa do Ambiente) survey from 2018 and a regional bathymetry. The first dataset, with a resolution of 10 m, covered from -0.5/-1 m to -8 m below MSL. The second one, extracted from MIRONE (Luís, 2007), has a 10 m resolution as well, and it extends up to the offshore border of the numerical grid.

At Praia de Faro, the non-hydrostatic XBeach model was implemented in a cross-shore profile to compute the overtopping indicators in the seaside edge of the wooden path (Figure 1 and Figure 2). The model setup was similar to the Quarteira model. The sea bottom elevation of the model was interpolated from several sources. The topography was extracted from a UAV survey conducted by the COSMO program in October 2018 that covered the emerged beach. The COSMO program also surveyed nearshore areas until -13.5 m MSL. A regional bathymetry extracted from MIRONE (Luís, 2007) was used to interpolate areas below -13.5 m.

2.4 Hazard assessment sources

Four sources found in the literature that characterize risk severity for pedestrians based on two overtopping indicators were gathered: Coastal Engineering Manual (CEM 2002), hereafter referred to as CEM, HIDRALERTA (Poseiro 2018), Eurotop (2018) and FLOODsite (2009) (Table 1). The last one uses maximum depth velocities (m^2/s), while for all others, the mean overtopping discharge (l/s/m) is used as an indicator to establish risk categories. The sources using the mean discharge as an indicator establish the most extreme risk level with discharges equal to or higher than 1 l/s/m. While CEM and HIDRALERTA determine four levels of risks, Eurotop (2018) only defines two levels (No risk and Risk). FLOODsite (2009) establishes also four risk levels.

Table 1. Risk level definition for pedestrians based on specific overtopping indicator limits.

CEM (l/s/m)				HIDRALERTA (l/s/m)			
Non-uncomf.	Uncomfort.	Dangerous	Very Dangerous	No injuries	Single minor injury	Multiple minor injuries	Serious injuries
<0.004	[0.004-0.03]	]0.03 – 1]	>1	<0.1	[0.1 - 0.5[	[0.5 - 1.0[	>=1
FLOODsite (2009) (m^2/s)				Eurotop (2018) (l/s/m)			
Low Caution	Vulnerable people	High dangerous for most	Extreme dangerous for all		No risk		Risk
<0.25	[0.25-0.50]	]0.5-1.1]	>1.1		< 1		>=1

2.5 Risk level characterization

To compare observed risks with the levels estimated by those four sources, a new risk level characterization is proposed that homogenizes all categories of those sources (Table 2). Four categories represented by a color scale, green, yellow, orange and red, corresponding to no risk, low risk, moderate risk and high risk, respectively, were considered. The definition of each color category is shown in Table 3. As Eurotop (2018) only defines two levels of risk, they were converted to green and red respectively and therefore the intermediate levels were not included.

Table 2. Proposed risk levels combining the four hazard assessment sources.

Source	Green	Yellow	Orange	Red
CEM	Non-uncomfortable	Uncomfortable	Dangerous	Very Dangerous
HIDRALERTA	No injuries	Single injury	Multiple minor injuries	Serious injuries
Eurotop (2018)	No risk	Not defined	Not defined	Risk
FLOODsite (2009)	Low caution	Vulnerable people	High dangerous	Extreme dangerous

Table 3. Risk level definition used for the characterization of the observed risks

No risk	No injuries or threats on individuals
Low risk	Minor injuries and caution with elderly and children
Moderate risk	Dangerous for most people.
High risk	Very dangerous for all

For each storm, the simulated indicator is used to establish the risk level based on Table 1, which is then converted to a color scale following Table 2. Later, the ability of each source is assessed by comparing risk observations to the computed risks, categorized according to Table 3. Among the five runs per storm, the maximum simulated indicator is used in Table 1 to establish the risk level.

3. RESULTS

3.1 Model results

The minimum, maximum and the average of the wave overtopping indicators of the 5 runs performed for each sea state are displayed in Table 4. In Praia de Faro, the highest values of mean overtopping discharges and maximum depth velocities were obtained on the 24th at 13:00 and 14:00. At these times, the maximum mean overtopping discharges exceeded 1 l/s/m and the maximum depth velocities were 1.63 and 1.15 m^2/s. It is important to remark that, among the 5 runs, the lowest values of the indicators obtained during these times are one or two orders of magnitude lower than the highest values of these indicators. Also, the mean value of the 5 runs do not exceed either 1 l/s/m or 1.1 m^2/s (the limits for the high risk level) for any of the simulated conditions (Table 4). For 11:00 and 16:00 simulations, the model did not compute wave overtopping at the target location. In Quarteira, the model did not simulate overtopping discharges at the target locations for storm Elsa. However, for storm Emma, the highest mean overtopping discharge and maximum depth velocity were 5.77 l/s/m and 2.22 m^2/s, Table 4.

Table 4. Model results. Overtopping indicator computed for the tested events at both study sites.

Praia de Faro							
Storm	**Mean overtopping discharge ($l.s^{-1}$ per m)**				**Maximum depth velocity (m^2 s^{-1})**		
	[Mix – Max]			**Average**	**[Mix – Max]**		**Average**
Lola, 24th, 11:00	0.0000	-	0.0000	0.0000	0.0000 -	0.0000	0.0000
Lola, 24th, 12:00	0.0600	-	0.2010	0.1408	0.1560 -	0.5860	0.3424
Lola, 24th, 13:00	0.0690	-	1.5240	0.7696	0.1760 -	1.6330	0.9644
Lola, 24th, 14:00	0.2440	-	1.2090	0.6250	0.3410 -	1.1490	0.7540
Lola, 24th, 15:00	0.0000	-	0.2250	0.0664	0.0000 -	0.3520	0.1224
Lola, 24th, 16:00	0.0000	-	0.0000	0.0000	0.0000 -	0.0000	0.0000
Quarteira							
Storm	**q ($l.s^{-1}$ per m)**				**Depth velocitiy (m^2 s^{-1})**		
	[Mix – Max]			**Mean**	**[Mix – Max]**		**Mean**
Elsa	0.0000	-	0.0000	0.0000	0.0000 -	0.0000	0.0000
Ema	3.7527	-	5.7723	4.5059	1.3101 -	2.2266	1.8126

3.2 Observed risk levels

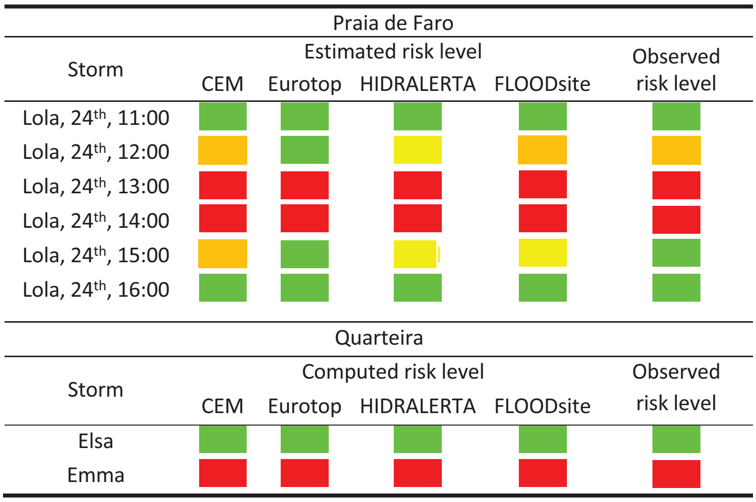
Based on the information gathered in the field and illustrated in Figure 2, the risk levels observed in Praia de Faro are defined as no risk at 11:00, 15:00, and 16:00 due to the absence of wave-induced flooding at these times (Table 5). The risk level is defined as moderate at 12:00 since the discharge can be dangerous for most people and high risk at 13:00 and 14:00 (Table 5) due to the large amount of water and high velocity of the flow as displayed in Figure 2. In Quarteira, the observed risk for Elsa is classified as no risk because the runup did not reach the urbanized area, while during storm Emma, the observed risk level is defined as high risk. It was postulated that the flow had a strong velocity and important magnitude that allowed the flooding to reach 100 m inland areas. Therefore, with these characteristics, this flow is dangerous for all, red level, (Table 5).

3.3 Risk level assessment

The overtopping indicators simulated for each sea state are used to determine the risk according to Table 2 and 3. In Praia de Faro, CEM estimates no risk at 11:00 and 16:00, moderate risk at 12:00 and 15:00 and high risk at 13:00 and 14:00 (Table 5). Eurotop (2018) estimates high risk at 13:00 and 14:00, while during the remaining time, it estimates no risk (Table 5). HIDRALERTA estimates no risk at 11:00 and 16:00, low risk at 12:00 and 15:00 and high risk at 13:00 and 14:00 (Table 5). The FLOODsite (2009) is slightly different and computes no risk at 11:00 and 16:00, low risk at 15:00, moderate risk at 12:00 and high risk at 13:00 and 14:00 (Table 5). The moderate risk level observed at 12:00 was correctly estimated by CEM and FLOODsite (2009) but they fail to estimate the risk level at 15:00. When comparing against observations, all sources characterize properly the high risk level conditions and the no risk conditions at 11:00 and 16:00. Only CEM and FLOODsite (2009) are able to estimate well the moderate risk conditions at 12:00. The no risk conditions observed at 15:00 are only well predicted by Eurotop (2018), while CEM overpredicts in two levels and HIDRALERTA and FLOODsite (2009) overpredict in one level.

In Quarteira, all the sources estimate properly the risk levels (green and red) as they fully match the observations (Table 5).

Table 5. Estimated and observed risk levels.



Praia de Faro					
Storm	Estimated risk level				Observed risk level
	CEM	Eurotop	HIDRALERTA	FLOODsite	
Lola, 24th, 11:00	🟩	🟩	🟩	🟩	🟩
Lola, 24th, 12:00	🟧	🟩	🟨	🟧	🟧
Lola, 24th, 13:00	🟥	🟥	🟥	🟥	🟥
Lola, 24th, 14:00	🟥	🟥	🟥	🟥	🟥
Lola, 24th, 15:00	🟧	🟩	🟨	🟨	🟩
Lola, 24th, 16:00	🟩	🟩	🟩	🟩	🟩

Quarteira					
Storm	Computed risk level				Observed risk level
	CEM	Eurotop	HIDRALERTA	FLOODsite	
Elsa	🟩	🟩	🟩	🟩	🟩
Emma	🟥	🟥	🟥	🟥	🟥

4. DISCUSSION AND CONCLUSIONS

This study demonstrates that the methodology applied here to estimate risk levels for pedestrians at these vulnerable sites is suitable for the development of an early warning system for wave-induced flooding. On one hand, the numerical framework employed in this study is able to capture the wave-induced flooding variability found in the observations. However, it is important to highlight that the variability observed in the model results as a consequence of the stochasticity effects of the wave overtopping process can not be neglected. Also, the mean value of the indicators would not be valid to compute the risk levels as high risk level conditions would not be identified in Praia de Faro. On the other hand, all sources investigated here are able to identify the high risk level conditions and are skillful in estimating no risk conditions. Therefore, both wave overtopping indicators are suitable to characterize risks. However, some differences are observed in the estimated risks for less energetic conditions (e.g. 12:00 and 15:00). Thus, for these conditions, CEM is the most conservative and estimates the greatest risk level (moderate risk) while Eurotop (2018) estimates no risk conditions. It would indicate that a new classification that unifies existing limits might be needed to better characterize these conditions. In future studies, more wave overtopping episodes should be monitored and modeled to further investigate the suitability of the existing and new limits of the wave overtopping indicators.

5. ACKNOWLEDGEMENTS

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