Development and validation of a process-based coastal flooding Early Warning System -Zarautz beach

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Abstract:
In the recent years, coastal cities exposure to storm impact have led to the development of Early Warning Systems, assisting authorities in the setting of their strategy to protect people and limit damages to buildings and infrastructures caused by coastal flooding. This study focuses on the development and validation of a process-based coastal flooding Early Warning System at the Zarautz beach, a highly urbanized embayed beach. The system estimates the hazard level through a scale that relates mean overtopping discharge values with hazard levels. The mean overtopping discharge is computed through a phase-resolving process-based numerical model that accounts for wave transformation processes in the nearshore zone and hydrodynamics induced by wave interactions with coastal structures. The assessment of the system accuracy is performed by comparing the computed hazard levels with those derived from images captured by a coastal videometry station during a series of potentially hazardous events with different intensities. The use of different hazard level estimation scales shows great variability in the system performance. The best system configuration shows an accuracy of 87% of hit, 4% of miss and 9% of fail. The results closely align with those achieved using the currently operational Early Warning System in Zarautz.

Keywords:
Early Warning System, Urbanized beach, Coastal flooding, Process-based models, Hazard level, Coastal videometry.

1. Introduction

The coastal flooding associated to storms can represent a critical challenge for coastal authorities with potentially significant consequences for both natural environments and human societies. Consequently, some coastal communities have been developing Early Warning Systems (EWSs) to anticipate the impact of incoming extreme events to improve and optimize their flood risk management strategy. However, detailed studies about the development and validation of EWSs are scarce. Current EWSs predominantly rely on either empirical formulations (STOKES *et al*., 2021; GAZTELUMENDI *et al*., 2016) or process-based numerical models (MERRIFIELD *et al*., 2021; POSEIRO, 2019; GARZON *et al*., 2023; DE SANTIAGO *et al*., 2023) to compute coastal flooding indicators. The former is most likely to be applied at regional scale due to its simplified approach. It usually requires intense site-specific calibration actions to obtain accurate results. This can limit their application to a limited range of hydrodynamic conditions and morphological configurations. Process-based EWSs provide a more comprehensive understanding of coastal flooding dynamics by explicitly considering the influence of climatic and morphologic parameters and coastal defences. The Basque coast, located in the northern Spain is composed of a series of highly urbanized and vulnerable embayed beaches that have experienced severe storm impact in the last decades leading to the development of the Basque Maritime Coastal Flooding Early Warning System (BMCEWS) (GAZTELUMENDI *et al.*, 2016). Since 2014, it is operated in real time by Euskalmet, the Basque meteorological agency. The BMCEWS consists in forecasting the hazard level for an incoming storm based on the computation of the Total Water Level (TWL). The waves contribution to the TWL, namely the wave runup, is computed using the well-known STOCKDON *et al*., (2006) empirical formulation that was calibrated for Zarautz beach. Comparisons with observations have highlighted the difficulty to transfer this type of EWS to other sites along the Basque coast. Indeed, this approach provides a valuable support to coastal authorities, but it still needs to be improved to account for the specificity of each site of interest along the Basque coast. In this study, we propose to develop a new EWS based on the application of a phase-resolving nearshore wave model to compute the mean overtopping discharge that is used as risk indicator consistently with several existing hazard level scales. The efficiency of this approach is assessed and compared with the BMCEWS using a unique set of hazard data collected through coastal videometry images at the Zarautz beach during variable hydrodynamics conditions.

2. Study area

The Zarautz beach is a 2 km long embayed sandy beach located at the Basque coast (Figure 1). The beach comprises two distinct sections: a dune-covered eastern portion and a western area bordered by a concrete seawall, rising from west to east. The beach has a double-barred morphology, transitioning between intermediate-dissipative and -

reflective states (DE SANTIAGO *et al.*, 2013), with an average slope of 0.02. The offshore wave climate is dominated by a mean significant wave height (Hs) of 1.5 m, a peak period (Tp) of 10 s and a main direction (θp) of 350º. Tides follow a semidiurnal pattern with a tidal range of approximately 3 m annually, reaching 4.5 m at maximum. The storm surge can vary between -0.5 m and 1 m in the study area (GONZÁLEZ *et al.*, 2004).

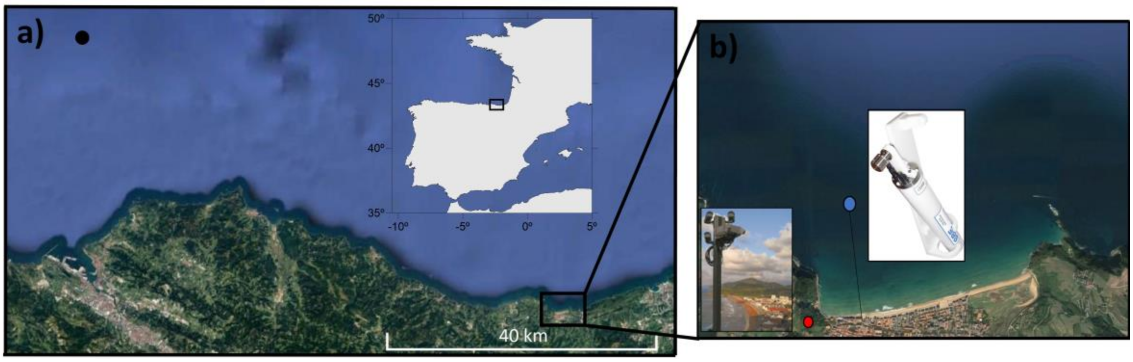

Figure 1. Study area. a) Location. Black rectangle: Zarautz beach. Black dot: Bilbao-Vizcaya wave buoy. b) Zarautz beach. Blue dot: Seabird. Red dot: Coastal videometry station. Black line: Studied profile.

3. EWS components

The proposed process-based EWS is composed of 3 modules (Figure 2) (1) the spectral Simulating Waves nearshore (SWAN) model to propagate wave conditions from deep to intermediate water depth, (2) the XBeach non-hydrostatic (XBNH) phase-resolving model to compute mean overtopping discharge and (3) a hazard level scale.

3.1 <u>SWAN model setup</u>

Nearshore wave conditions at intermediate water depth (Figure 3), 19 m off Zarautz, are computed with the phase-averaged third generation SWAN spectral waves model. The SWAN model (version 4131) is set-up in 2D stationary mode, with white capping, breaking, friction and quadruplet interactions activated. Three nested regular grids were created to propagate offshore wave energy density spectrums from the Bilbao-Vizcaya wave buoy position to the coast (Figure 2). The global grid is 122 km long and 40 km wide with 1 km of resolution starting at a depth of around 580 m. From a depth of approximately 150 m, a regional grid of 61 km long and 23 km wide with a resolution of 250 m is nested to the global one. Finally, at 50 m depth until the shoreline, a local grid of 8 km long and 4 km wide with a resolution of 50 m is nested.

3.2 <u>XBNH model setup</u>

The transformation of waves in the nearshore zone and the overtopping discharge are computed with the XBNH (version 1.23.5983 known as XBeachX) in 1D mode. The model is forced with the SWAN model output spectra (Figure 2) converted into free surface timeseries applying random phases to each frequency component and water level variations. The bed profile was obtained from a topobathymetric field survey carried out between the 3rd and 4th of March of 2021 at 2 m resolution, covering the area from the promenade until 30 m depth. Irregular mesh size was implemented in the cross-shore direction, varying from 4.5 m at the offshore boundary to 0.5 m at the shore. The Courant–Friedrichs–Lewy (CFL) condition was set to 0.7. A Manning coefficient of n=0.02 s/m$^{1/3}$ was adopted. The rate of surface rise steepness (maxbrsteep) before breaking was set to 0.3. The XBNH results are processed to provide the averaged value of mean overtopping discharges at the promenade among 10 simulations varying the wave phase randomly (Figure 2).

3.3 Hazard level scale

Different scales were implemented including the Coastal Engineering Manual (CEM) scale (BURCHARTH & HUGHES, 2003), the Eurotop scale (VAN DER MEER *et al.*, 2016), the HIDRALERTA scale (POSEIRO, 2019), the Floodsite scale (PRIEST *et al.*, 2008) and the most recent EW-Coast scale (GARZON *et al.*, 2023). Each scale, relates the mean overtopping discharge over an hour with different warning levels associated with urban components and buildings, ranging from: i) Level 0: No damage (green), ii) Level 1: Minor damage (yellow), iii) Level 2: Damage (orange), iv) Level 3: Severe damage (red). The most severe alert among each event is selected as output (Figure 2).

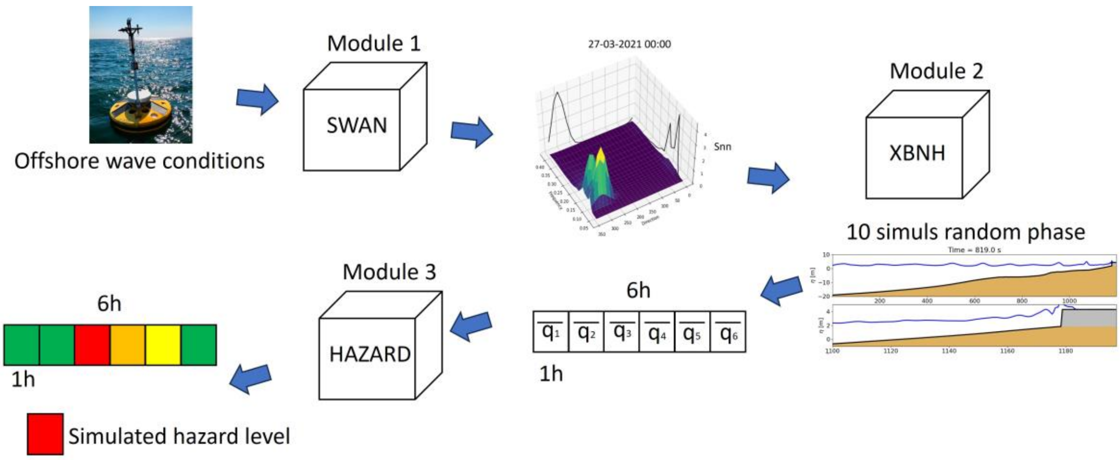

Figure 2. EWS workflow by inputs, modules and outputs.

4. Hazard data

Offshore wave conditions (Figure 3) during the study period (24feb2021-1apr2021) were measured by the Bilbao-Vizcaya wave buoy (Figure 1, a) moored at 600 m depth. The buoy provides energy density spectrums that are used as input of the SWAN model. The Total Water Level (TWL) elevation at the coastline is computed to identify potentially hazardous events. It was calculated by superimposing water level measured with a Seabird (Figure 1, b) moored at 19 m and wave runup calculated using the STOCKDON *et al.* (2006) empirical formulation forced with offshore Bilbao-Vizcaya wave buoy measurements assuming a constant beach slope of 0.02. Potentially hazardous events were determined based on the minimum TWL threshold value required to cause overtopping (observed in images). This criterium results in 22 potential hazardous events of 6 hours that occurred around high tide cycles (Figure 3).

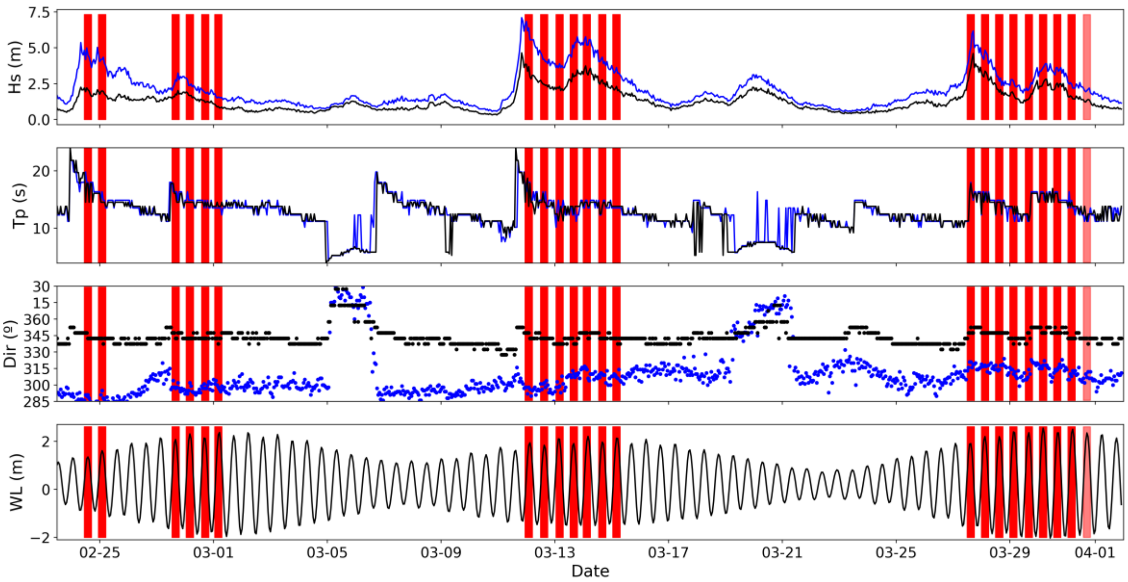

Figure 3. Hydrodynamic data (24feb2021-1apr2021). Blue: Offshore waves measured with Bilbao-Vizcaya wave buoy. Black: Nearshore waves computed with SWAN and water level measured with Seabird. Red rectangles: identified 22 hazardous events.

The hazard level of each event was defined by the alongshore extension of overtoppings, identified as water sheets or sediment deposit at the promenade (Figure 4, white dashed polygon) observed on images recorded by the video station operated at Zarautz (Figure 1, red dot). Indeed, since the elevation of the promenade significantly increases from west to east (4 m to 9 m), it is assumed that the hazard level increases with the alongshore extension of overtoppings. The validity of this hypothesis was verified by comparing the transect with the highest altitude that has been overtopped (Figure 4, red transects) on images with the amount of economic damage reported by the Spanish Insurance Consortium (Figure 4, images header) for 6 storms between 2010 and 2015 along the Basque coast. The results demonstrate that bigger overtopping extension led to higher economical amount of damage (Figure 4). Most of the damage was associated to civil work followed by commerces and stores.

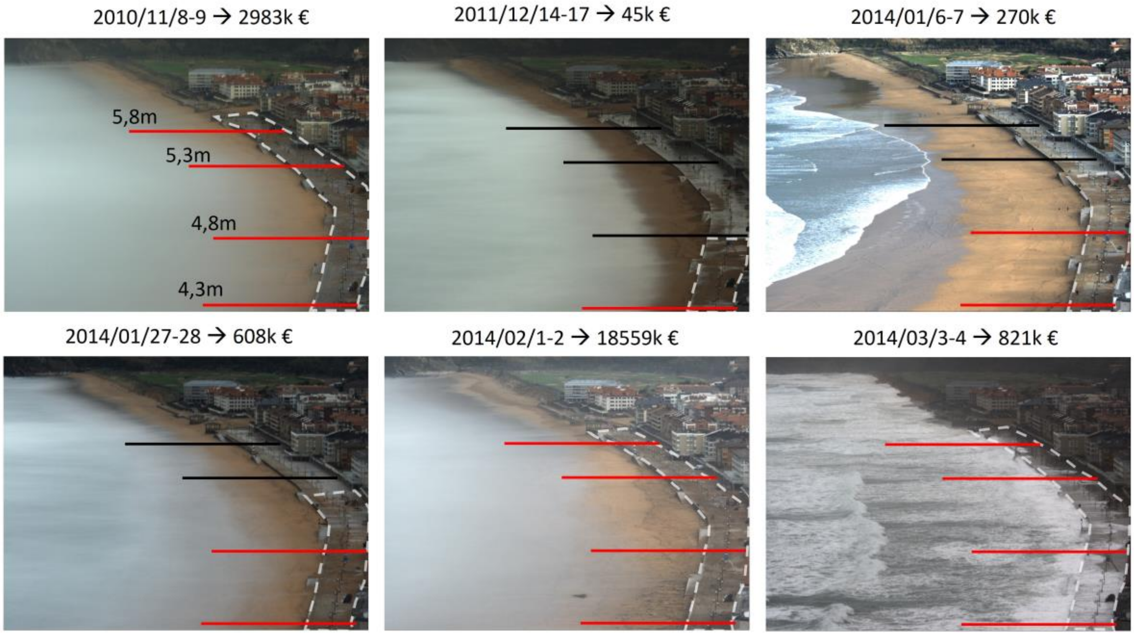

Figure 4. Coastal videometry images with economic damages at the header. White dashed polygon: promenade area covered by water sheets or sediment. Black and red lines: transects not fully and fully overtopped respectively with their elevation above.

Linear logarithmic regression analyses between the economic amount of damage and the altitude of the highest transect overtopped define the hazard levels as: i) Level 0 (green): No damage, costs below 70.000€ along the Basque Coast associated to overtopping below 4.3 m, ii) Level 1 (yellow): Minor damage, costs between 70.000-200.000€ along the Basque Coast associated to overtopping between 4.3 m and 4.8 m, iii) Level 2 (orange): Damage, costs between 200.000-3.000.000€ along the Basque Coast associated to overtopping between 4.8 m and 5.8 m, and iv) Level 3: Severe damage, costs higher than 3.000.000€ along the Basque Coast associated to overtopping above 5.8 m. This categorisation was applied to obtain the hazard level on the video images recorded at the 22 hazardous events identified during the study period.

5. Results

Figure 5 shows the comparison between hazard levels computed with EWSs using different hazard scales, the BMCEWS that is currently operated in the Zarautz beach and video derived hazard levels. The implementation of different hazard scales shows great variability in the EWSs accuracy. The percentage of hit (alerts matched), miss (alerts overestimated) and fail (alerts underestimated) reveals that the implementation of the EW-Coast (GARZON *et al*., 2023) hazard scale provides the most accurate results. Its application leads to 87% and 50 % of hit, 4% and 17% of miss and 9% and 33% of fail for all the events (blue dots) and for alerts equal or higher than Level 1 (red dots) respectively. The other hazard scales give significant higher percentage of miss, from

higher to lower, and so, best to worst performance, CEM, HIDRALERTA, EUROTOP and FLOODSITE. The fail percentage is relatively constant due to the small number of alerts compared (5) to the total amount of events (22). The EW-Coast scale (Figure 5, b, blue stars) matches most of the alerts despite of two events where it slightly under- (green-yellow) and over-estimates (yellow-green) the observed hazard and a single event where the underestimation increases (green-yellow).
The BMCEWS (Figure 5, B, grey dots) provides similar results to the EWS with EW-Coast scale (blue stars). The hit-miss-fail percentages are identical for all the events. By using the BMCEWS most of the hazard levels are well matched despite of a single event significantly underestimated (yellow-orange) and two events where a slight over- (yellow-green) and underestimation occurs (green-yellow).

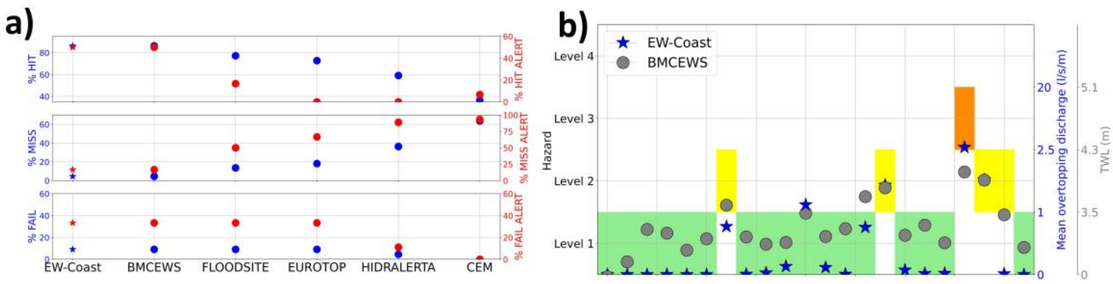

Figure 5. EWSs validation. a) Hit-miss-fail percentages. Blue: All the events. Red: events with alerts higher than Level 0. b) EWSs computed (stars, dots) and observed (filled squares) hazard levels for EW-Coast and BMCEWS. Left y axis: Hazard level. Right y axis: Mean overtopping discharge and TWL thresholds.

6. Discussion and conclusions

The present study shows the development of a new EWS based on the combination of a phase-resolving model and a hazard scale. The forecasted hazard levels are then compared with a unique set of hazard data collected through coastal videometry images.
The selected hazard scale has significant influence in the EWSs performance. The EW-Coast scale provides the best results while the others significantly overestimate the hazard level. This fact highlights the relevance of adequate validation datasets to ensure the EWSs good forecasting skills.
Comparing the developed EWS with the BMCEWS, a similar performance is obtained. The difficulty to transfer the latter to other sites is related to a specific calibration process. The former presents a promising potential to be transferred.

Acknowledgments

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