DEVELOPMENT OF AN EFFICIENT EARLY WARNING SYSTEM FOR WAVE-INDUCED FLOODING

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INTRODUCTION

Coastal flooding, particularly due to wave-induced flooding or overtopping occurs when runup surpass coastal defences, often occurring during high tides and surges. This phenomenon poses significant risks to urban elements, disrupting local services and transport, and endangering lives. Anthropogenic pressures, rising sea levels, and potential increases in storminess are expected to enhance these risks in the future.

To protect coastal communities, early warning systems (EWSs) are essential, providing crucial information to anticipate and alert for hazardous situations. EWSs are vital for coastal planning, disaster risk reduction, and climate change adaptation, offering timely and accurate information to save lives and prevent economic and environmental losses. Despite the high benefit-to-cost ratio demonstrated in economic analyses, there are few examples of EWSs for coastal flooding worldwide (e.g., Garzon et al., (2023); Harley et al., (2016) and Stockdon et al., (2023)).

The goal of this study was to develop, test, and implement an operational wave-induced flooding early warning system for sandy beaches supported by machine learning techniques. Thus, the philosophy underpinning the conceptualization of this EWS for coastal zones was to minimize the time required to generate operational warnings, while providing end-users with robust scientifically based information obtained from open sources and state-of-the-art numerical models and data-driven techniques. To achieve this, the systems were designed to function in two different phases, the development phase and the operational phase (Figure 1).

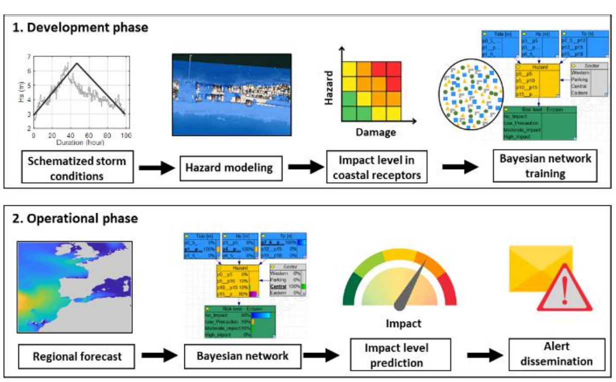

Figure 1 – Overview of the EWS for coastal zones with the two functional phases.

STUDY AREA

The study area is the urbanized stretch of Praia de Faro, an open sandy beach located in the Ria Formosa barrier island system on the southern coast of Portugal. Regarding the wave climate, the site is exposed to the dominant and more energetic wave conditions (W-SW) and sheltered from the less energetic E-SE waves. The oceanfront is protected either by walls and rocks (mostly buried by sand) or by a natural beach-dune system. The area was divided into four sectors (western, parking, central, and eastern) according to their morphology and exposed elements.

DEVELOPMENT PHASE

The development phase (Figure 1, upper panel) involved several tasks:

1) Schematization of all the possible events impacting the site (ensuring a comprehensive range of oceanic boundary conditions);
2) Modeling of the overtopping occurrences driven by these oceanic boundary conditions by using a numerical framework consisting of SWAN and XBeach (non-hydrostatic mode). This allowed the propagation of the wave conditions, from offshore to the coast and the simulation of individual wave overtopping episodes. Four cross-shore profiles were considered for of XBeach simulations, to represent the conditions in the four sectors of the studied area;
3) Assessment of the overtopping impacts on three coastal assets, namely pedestrians, buildings, and vehicles. The system categorizes the impact into four levels (no, low, moderate and high impact) according to the conceptual description provided by Garzon et al. (2023b). The mean overtopping discharge simulated by the numerical model framework was employed as a proxy to categorize wave overtopping impacts at each sector and receptor according to the limits proposed by Garzon et al. (2023b);
4) Building Bayesian Networks (BNs) to act as a surrogate of the previously generated information. A Bayesian Network is a probabilistic multivariate model that provides a probability distribution of the occurrence associated to each possible impact. The relationship between the variables is derived from prior knowledge regarding the ocean boundary conditions, sectors and impacts.

VALIDATION ASSESSMENT

The predictive skills of the EWS were assessed by comparing the predicted impact level with the observed level for approximately 100 overtopping and quasi-overtopping events reported in the study area. The accuracy of the system varied between 76% and 87%, depending on the asset (Table 1). Over-prediction accounted for 21% of the cases for pedestrians and for only 8% of the cases for vehicles. Underprediction generally accounted for a small percentage of the cases. The F1 score indicated that the system achieved better performance for the no impact and high impact levels (Table 1).

	Pedestrians	Vehicles	Buildings
Impact level	F1 score	F1 score	F1 score
No impact	0.85	0.93	0.96
Low impact	0.20	0.47	0.44
Mod. impact	0.27	0.40	0.58
High impact	0.88	0.90	No data
True positive	76%	87%	84%
Overestimation	21%	8%	11%
Underestimation	3%	5%	4%

Table 1. EWS predictive skill metrics

IMPLEMENTATION PHASE

After the completion of the development phase and its verification, the operational phase can be started. It consists of four main steps (Figure 1, lower panel): downloading and extracting the oceanic variables such as water levels and wave conditions from the regional forecasts, introducing these variables into the previously trained BNs, obtaining the impact predictions and disseminating the early warnings by e-mail to the final end-users. The daily flooding impact predictions are generated almost instantaneously based on the latest oceanic forecast information and cover the next 72 hours.

The entire process was implemented in the HIDRALERTA architecture (Fortes et al., 2020) and runs autonomously, i.e., only requiring human intervention to solve computational issues (e.g. problems with the functioning of the cluster where HIDRALERTA is running) or issues with the offshore forecasts. An example of a warning from HIDRALERTA system is illustrated in Figure 2.

CONCLUSIONS

The Bayesian Network + state-of-the-art numerical modeling approach was able provide quasi-instantaneous hourly forecasts for the next 72 hours with a high degree of accuracy. Praia de Faro was chosen as a demonstration site, but other urbanized areas fronted by sandy beaches can benefit from similar EWSs. The two-phase approach is very flexible, enabling the system to be updated with new oceanic conditions, varying beach morphology characteristics, human occupation and social behavior. Also, longer forecast periods can be requested if needed. This system constitutes a powerful tool for disaster management, and thus, the knowledge and methodology developed in this study contribute to the development of reliable EWSs, that will ultimately reduce the impact of extreme oceanic events in coastal communities.

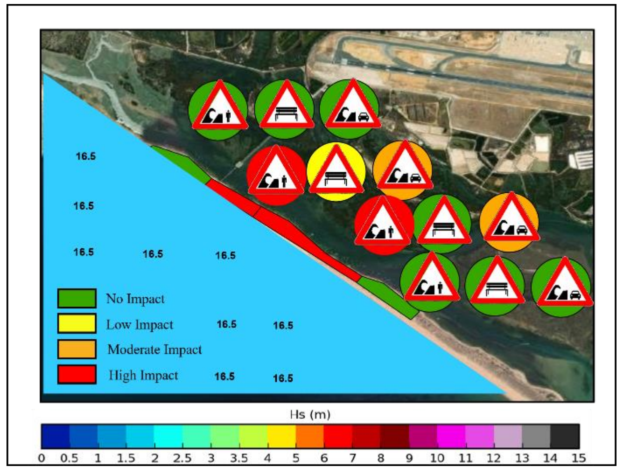

Figure 2 – Warning created by the coastal component of HIDRALERTA for Praia de Faro (flooding).

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