# Assessing wave-induced flooding risks at the Algarve coast for current and future conditions

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**Abstract:** Wave-induced flooding represents a threat and sea-level rise will exacerbate the problem. Bayesian Network tools that surrogate hydrodynamic and risk models were designed to predict risks induced by overwash/overtopping at Praia de Faro and Quarteira (Portugal) for current and future conditions. A 23.5 year-dataset of oceanic conditions for the 1996-2020 period was used to assess the average number of hours per year (h/yr) with risks for coastal receptors today. Then, sea-level rise projections from IPCC were considered to compute h/yr with risks by 2050 and 2100. The results revealed that today, the risk for pedestrians at Praia de Faro is higher than at Quarteira (13 h/yr against 1 h/yr) and is expected to increase by a factor of 2 by 2050 and by 4-6 times by 2100. At Quarteira, the risk conditions for pedestrians are not anticipated to change by 2050, but are expected to increase by a 3-4 factor by 2100.

**Keywords:** Bayesian network, coastal flooding, sea-level rise, wave overtopping, XBeach.

## 1. INTRODUCTION

Coastal flooding is threatening many low-lying areas while population growth exacerbates the risks. This is particularly relevant for low-lying areas, where waves overtopping coastal defences (e.g. seawalls or dunes) can induce important damage in hinterland areas. Also, the vulnerability of coastal communities is projected to highly increase in a scenario of climate change, with sea-level rise (SLR) being one of the main agents responsible for enhancing the risks (Vousdoukas *et al*., 2018). SLR will contribute to increase the frequency and magnitude of the flood events (Ranasinghe, 2016). Therefore, if adaptation measures to climate change are not implemented, vast new areas can be impacted by coastal floods while others will face an increase in flood intensity and occurrence.

Several approaches, such as artificial neuronal networks (Coeveld *et al.*, 2005), empirical formulae (EurOtop, 2018), physical models (Geeraerts *et al.*, 2007), numerical models (Manz, 2021) and statistical tools (Plomaritis *et al.,* 2018), are available to compute wave-induced overtopping over a coastal structure that can result in a flood event. Among those approaches, Bayesian Networks (BNs) are probabilistic models that examine the correlation between variables and can be used to predict coastal applications (after training). These systems are data-intensive, requiring large input information to derive the probabilistic relationships used in their predictions. Under the lack of field observations, calibrated and validated process-based models can be used to generate the required information.

Within the EW-Coast project (Garzon *et al.*, 2022), BNs were designed to predict risks associated with coastal storms at two sites on the Southern coast of Portugal: Praia de Faro and Quarteira. In this study, the BNs previously developed for both sites were used to investigate the risks associated with coastal flooding for pedestrians, properties and vehicles considering present and future conditions.

## 2. STUDY CASES

Praia de Faro is an open beach located in the Peninsula of Ancão, a narrow sand barrier that separates the Atlantic Ocean and a coastal lagoon. The average beach slope is around 0.10 during calm conditions (Vousdoukas *et al.*, 2012). The area investigated here is in front of a parking lot, where a walking wooden path marks the edge of the urbanized area (Fig. 1a). The elevation of this path is 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). Quarteira is located ten kilometres NW from Praia de Faro. This is an urban beach with rocky groins and limited by a promenade (Fig. 1b) with an elevation of 5.5 m above MSL at the backside. This site has a similar average beach slope, 0.10, and a beach width of more than 60 m (Garzon *et al.*, 2020). Both sites are exposed to W–SW wave dominant conditions and are relatively protected from E–SE. Therefore, only storms with directions greater than 180º N can create flood conditions (Ferreira *et al.*, 2021). The mean tidal range in the region is about 2.2 m, with maximum ranges of 3.5 m during spring tides.

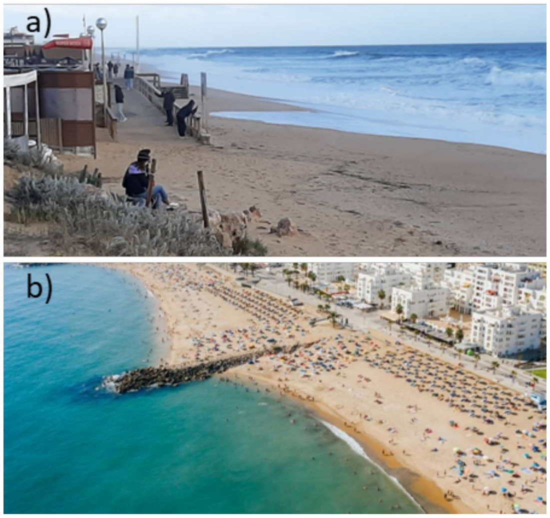

*Fig. 1. a) Wooden path at Praia de Faro (source: authors) and b) the promenade at Quarteira (source: Google).*

## 3. METHODS

### *3.1. Bayesian network training*

Based on the 23.5 years of input data, the Bayesian Networks evaluated the correlation between the input variables and risks in coastal receptors. To create comprehensive information to train the BNs, a numerical framework that computes wave overtopping was coupled with a risk model to identify risk conditions induced by a set of synthetic sea states or events.

The considered input variables of the sea states were significant wave height (Hs), peak wave period (Tp) and total water level (TWL). The synthetic events were built by combining a wide range of these three input variables. Regarding Hs and Tp, the values ranged from 1 m to 9 m and from 8 s to 19 s, respectively, while the considered TWL variability was between 0.25 m and 2.5 m (above MSL). The lower limits were selected based on the authors' experience and field observations (more than 20 years at Praia de Faro). The upper limits correspond to return periods of the order of 100 years for both Hs and TWL, and to the maximum recorded value of Tp. Then, the variables defining the sea states were discretized in bins of 0.5 m and 1 s for the wave parameters, and in bins of 0.25 m for TWL. This discretization of the wave variables allowed to include in the analysis two types of events: 1) storm events characterized by Hs larger than 3 m and 2) swell events whose Hs is lower than 3 m and Tp is higher than 13 s.

These events were implemented in SWAN, which downscaled the wave conditions from deep water to nearshore areas, where XBeach (one-dimensional 'non-hydro' model, Roelvink *et al.*, 2009) simulated nearshore wave processes and run-up incursions. After a warm-up period, all XBeach runs simulated 600 waves that multiplied by their mean period, estimated with the up-crossing method, resulted in the time used to compute the mean wave overtopping discharge (q). To better account for the stochastic effects of the wave overtopping process and obtain risk probability information associated with each storm condition, five synthetic storms, with their values randomly selected, were included to train each bin of the BNs.

Regarding the risk model used to create the training data, EurOtop (2018) provides recommendations for tolerable overtopping limits for pedestrians, vehicles (cars) and properties (potentially weak elements like doors and windows) as displayed in Tab. i. Using these limits, the mean discharge simulated by XBeach was used to establish risk conditions. Among the 5 storms within each bin, the risk was defined based on the worst-case scenario.

*Tab. i. Mean wave overtopping discharge (q) limits for establishing risks in coastal receptors.*

| | Pedestrians | Properties | Vehicles |
|---|---|---|---|
| q (l/s · m) | 0.3 | 1.0 | 5.0 |

### *3.2. Oceanographic data*

Oceanographic data used into the BNs consisted of hourly wave climate, astronomical tides and storm surges corresponding to the 23.5-year period of 1996-2020. Then, the average number of hours per year (h/yr) with risk conditions was calculated. The wave parameters, such as Hs, Tp and direction, were collected by the Faro Buoy, at 100 m depth. The surge data were measured at the Huelva tidal gauge, located 60 km from the sites, and the astronomical tide was extracted from XTide (https://flaterco.com/xtide/). The effects of climate change, namely the rise of the mean sea level, are incorporated by adding to the astronomical tide the sea-level-change scenarios presented by IPCC (Masson-Delmotte *et al.*, 2021) at the station of Lagos, southern Portuguese coast (https://sealevel.nasa.gov/ipcc-ar6-sea-level-projection-tool). Thus, the number of h/yr with risk conditions was evaluated for 5 scenarios: present conditions and both the SSP2-4.5 (intermediate future Greenhouse Gas Emissions) and SSP5-8.5 (very high future Greenhouse Gas Emissions) scenarios for 2050 and 2100. The projected SLRs for those scenarios at mid-century are, respectively, 0.23 m and 0.26 m, while by the end of the century, changes of 0.6 m and 0.8 m are expected. Wave parameters and surge stationarity were considered and the same dataset of oceanographic conditions (1996-2020) was used to calculate the h/yr for future conditions, with the astronomical tide input varying according to each studied IPCC scenario. Furthermore, it was assumed that the crests of the flood defences and the beach morphology will not be altered (i.e., no adaptation).

## 4. RESULTS AND DISCUSSION

At Praia de Faro, for the 23.5-year period (~206000 hours) evaluated here, 307 hours have shown potential risks for pedestrians, 174 hours for properties and 22 hours for vehicles, under present conditions. This total number of hours corresponds to 13 h/yr under risk conditions for pedestrians, 7 h/yr for properties and 1 h/yr for vehicles (Tab ii). For the 23.5 years with the IPCC 2050 scenarios, the projected h/yr with risks for pedestrians and properties will approximately double the present ones, with the very high gas emission scenario accounting for 2 h/yr more with risks for both receptors than the intermediate one (Tab ii). The expected risks for vehicles will increase until 2-3 h/yr with SSP2-4.5 and SSP5-8.5 scenarios, respectively. By the end of the current century and under an intermediate gas emission scenario, the number of hours per year with risks for pedestrians and properties will be multiplied by 4-5 in relation to present conditions, while for vehicles, it will increase by 10 times. On the other hand, for a very high gas emission scenario, the number of h/yr with risks for pedestrians and properties will increase by factors of 6 and 7 and the vehicles by a factor of 16 in regard to the present (Tab ii). The increase of hours with risks found here for 2050 and 2100 scenarios is larger than the hazard increase found by Ferreira *et al*. (2021) for Praia de Faro, as they projected a rise in events' frequency of 1.5 and 2.7 for those years, respectively. Nevertheless, these projected events will last longer as the SLR will induce a longer duration of overtopping. Thus, it is expectable that the increase in duration is higher than the increase in the number of events.

*Tab. ii. Number of hours per year (h/yr) under risk conditions. Values in [] indicate the two IPCC scenarios assessed.*

| | Praia de Faro | | |
|---|---|---|---|
| | Pedestrians | Properties | Vehicles |
| Present | 13 | 7 | 1 |
| 2050 | [25 - 27] | [14 - 16] | [2 - 3] |
| 2100 | [53 - 73] | [35 - 49] | [10 - 16] |
| | Quarteira | | |
| | Pedestrians | Properties | Vehicles |
| Present | 1 | < 1 | < 1 |
| 2050 | [2 - 2] | [1 - 1] | [< 1 - < 1] |
| 2100 | [3 - 4] | [2 - 3] | [< 1 - < 1] |

The nature of the event, storm or swell conditions, inducing coastal flooding and its evolution along the century were further investigated at Praia de Faro. For present conditions, risk events for pedestrians were dominated by storm events while the swell events promoted risks only 1/4 of the hours. For properties and vehicles, only 10% and 5% of the risk situations were induced by swell events, respectively (Fig. 2). For the 2050 very high gas emission scenario, swell events will induce more than 1/3 of the hours under risk conditions for pedestrians and about 15% for properties and vehicles (Fig. 2). For the 2100 scenario, both events (storm and swell) will contribute similarly to the number of hours per year with risk for pedestrians, but storm conditions will induce about 2/3 of the risk situations for properties and vehicles (Fig. 2).

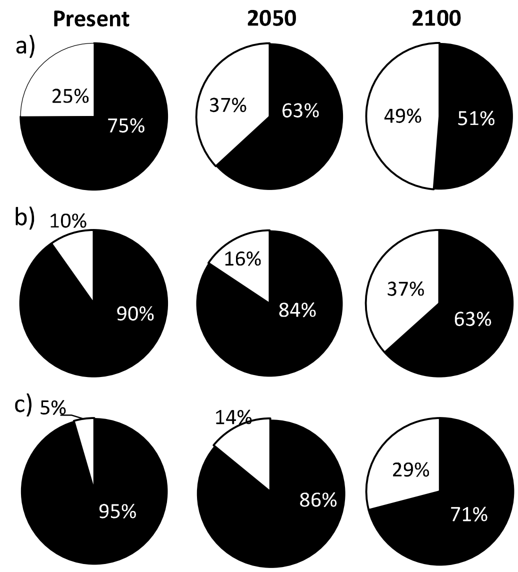


*Fig. 2. Hour distribution of risk for pedestrians (a), properties (b) and vehicles (c) for present and future conditions under the SSPS4-8.5 scenario at Praia de Faro. Black corresponds to storm events and white to swell events.*

At Quarteira, for present conditions, the number of h/yr under risk conditions is remarkably lower than that at Praia de Faro, with only 1 h/yr for pedestrians and less than 1 h/yr for properties and vehicles (Tab ii). For the two 2050 gas emission scenarios, the hours with risk will slightly increase by 1 h/yr for pedestrians and properties while vehicles will not experience more hours per year under risk. For the 2100 scenario, for the intermediate gas emission scenario, pedestrians and properties will be subject to 3 h/yr and 2 h/yr, respectively, and for the high gas emissions scenario, the risk situations will increase up to 4 h/yr and 3 h/yr. Vehicles will not experience more than 1 h/yr under risk by 2100.

For present conditions, at Quarteira, the risk conditions for pedestrians were driven mainly by storm events (89%). Conversely to Praia de Faro, the impact of swell events at this site is not expected to significantly increase over the century (Fig. 3).

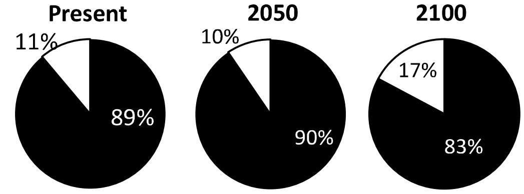


*Fig. 3. Hour distribution of risk for pedestrians for present and future conditions under the SSPS4-8.5 scenario at Quarteira. Black corresponds to storm events and white to swell events.*

## 5. CONCLUSIONS

The information generated by the EW-Coast project was used to assess the vulnerability of coastal receptors at two sites on the southern coast of Portugal. Pedestrians at Praia de Faro were found to be importantly more vulnerable than at Quarteira for current conditions (13 h/yr against 1 h/yr). Moreover, risk conditions for this receptor are expected to increase by a factor of 2 by the middle of the century and by 4-6 times until 2100. Pedestrians at this site are more exposed to storm events today, but swell events will increase their contribution to coastal flooding through the century until reaching a similar contribution to that of the storm events. At Quarteira, the risk conditions for pedestrians are not anticipated to change significantly by 2050, and by 2100 they will increase by a 3-4 factor. However, the number of hours per year with risks is expected to be remarkably lower than at Praia de Faro by 2100 (4 h/yr against 73 h/yr in the SSPS8-8.5 scenario). Also, at Quarteira, the risk situations will be mainly caused by storm events.

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