



Uncertainty induced by hydrodynamic and morphological boundary conditions in Coastal Flood Early Warning System predictions

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Abstract. Early Warning Systems (EWSs) are increasingly used to support coastal flood risk management, yet uncertainties in hydrodynamic and morphological boundary conditions can substantially affect forecast reliability. This study investigates the impact of hydrodynamic forcing and beach profile characteristics on coastal flooding hazard predictions using a validated process-based EWS in Zarautz beach (Basque Country, Spain). A database of 2,880 simulations was generated by combining representative storm conditions and synthetic beach profiles spanning the observed hydrodynamic and morphological variability of the study area. Univariate and multivariate sensitivity analyses were performed to quantify the influence of individual boundary conditions and their interactions on predicted hazard levels. The effects of realistic acquisition errors in operational wave forecasts and real-time morphological observations were also assessed using historical storm events. Results show that the uncertainty on hazard level predictions is predominantly controlled by the variability in hydrodynamic boundary conditions, which can alter predicted hazard levels by up to three levels, whereas morphological variability leads to changes of up to two levels. Among morphological parameters, beach slope and dry beach width exert the strongest influence. The role of morphology strongly depends on the hydrodynamic regime: under energetic wave conditions or low seawall freeboard configurations, hazard predictions become largely insensitive to morphological variability, whereas morphology plays a greater role under low-to-moderate forcing and high seawall freeboard conditions. Operational analyses indicate that extreme hydrodynamic errors remain the dominant source of variability. Regarding average hydrodynamic and morphological acquisition errors, hydrodynamic errors have a slightly stronger influence, however, morphological errors generate comparable forecast uncertainty. These findings provide practical guidance for optimizing beach monitoring strategies and improving the reliability of coastal flood EWS predictions.



1 Introduction

30 Coastal flooding occurs when seawater submerges normally dry, low-lying coastal land. It poses a significant threat to communities worldwide, driven by intense urbanization of coastal areas and the impacts of climate change, such as rising sea levels, increased storm intensity, and changing weather patterns (Vousdoukas et al., 2016; Vitousek et al., 2017). To safeguard coastal communities, effective modelling tools are crucial for anticipating and mitigating the growing threat of flooding. Short-term risk reduction can be achieved through Early Warning Systems (EWS) as decision-support tools. Those
35 systems provide valuable information to anticipate potential storm hazards and assist local authorities in deploying appropriate mitigation solutions.

EWSs compute coastal flooding through a range of indicators, including the flood depth (Ferreira et al., 2017), percentage of flooded area (Gallien et al., 2018, Sánchez-Artús et al., 2025), total water level elevation (Toimil et al., 2023, Chatzipavlis et al., 2026), overtopping discharge (Garzon et al., 2023b), number of overtoppings (de Santiago et al., 2023) and individual
40 maximum overtopping volume (Stokes et al., 2021). The criteria to determine the hazard level then relies on thresholds values of coastal flooding indicators. On the one hand, there are studies defining site-specific threshold values from the relation between visual observations of the hazards (Merrifield et al., 2021) or amount of economic damage (Gaztelumendi et al., 2016) with the computed Total Water Level (TWL) elevation for a specific site. On the other hand, there are studies defining threshold values for specific coastal typologies and elements, (Van der Meer et al., 2016, Poseiro, 2019, Burcharth
45 and Hughes, 2003, Priest et al., 2008) from the relation between coastal flooding hazards defined through experience and expertise with measurements of the mean overtopping discharge.

EWSs predictions rely on various physical boundary conditions, including the beach morphological information and the hydrodynamic data of incident events. If these conditions are not accurately represented, they can introduce uncertainty into the results and the subsequent decisions based on them (Xu et al., 2023). Hydrodynamic boundary conditions are typically
50 derived from wave and water level forecasts, which may contain inaccuracies at specific locations, often underestimating wave heights during energetic wave conditions (Callens et al., 2020). Morphological boundary conditions can be gathered from in situ measurements. Ideally, updated bathymetry should be collected immediately before a storm to update the forecasting model. However, conducting repeated bathymetry surveys on short notice as a storm approaches is logistically challenging and generally not feasible in most locations (Matheen et al., 2021). Coastal videometry images can also be used
55 to remotely extract real-time morphological information as a storm approaches, but they require constant human supervision and are less accurate than in situ surveys, especially for subtidal information. Consequently, morphological boundary conditions are often defined as time-invariant "representative" or "synthetic" (Matheen et al., 2021, Abalia, 2025) morphology based on historical data, which may differ from real-time measurements.

There are few studies in the literature that assess the uncertainty in EWS predictions caused by using synthetic morphologies
60 to represent the beach profile. de Santiago et al. (2023) examined the effects of adjusting Dean (Dean, 1991) and Hsu (Hsu



and Evans, 1989) beach profiles to historical subtidal profiles on EWS predictions at Zarautz beach. They found significant variability in EWS predictions for different profiles under the same hydrodynamic conditions, with hazard levels differing by up to two levels. Garzon et al. (2023a) evaluated the uncertainty of using various representative profiles, ranging from pre-storm to heavily eroded profiles with two intermediate profiles, based on historical data in EWS predictions at Faro beach. 65 They discovered that the hazard level varied by one level depending on the profile used.

Studies have also quantified the uncertainty of neglecting erosion during storms (Phillips et al., 2017; Cueto Fonseca et al., 2021; Toimil et al., 2023) or morphological variability (Cohn and Ruggiero, 2016; Gomés et al., 2020) on process-based model outputs. Phillips et al. (2017) and Cueto Fonseca et al. (2021) reported that ignoring morphological changes can lead to underestimations of wave overtopping volumes of up to 39% and flooded areas of up to 15%, respectively. Similarly, 70 Toimil et al. (2023) showed that neglecting short- and long-term erosion may produce substantial over- or underestimations of TWL and flooded areas. In addition, short-term erosion was found to reduce both TWL values and dune crest and toe height, however, the counteracting effects of these changes resulted in only minor differences in the flooded area. Cohn and Ruggiero (2016) found that seasonal and interannual variability in nearshore sandbars and beach topography affected wave runup by up to 0.18 m and 0.64 m, respectively. However, these studies were based on univariate analyses of the uncertainty 75 induced by beach morphology on coastal flooding indicators.

The present study aims to quantify the uncertainty in coastal flood EWS predictions arising from variability in physical boundary conditions in a highly urbanized coastal area. The results provide insights into the relative influence of hydrodynamic and morphological boundary conditions on predicted hazard levels, with direct implications for the operational implementation of coastal flood EWSs. In addition, this study will provide meaningful insights on the capability 80 of the beach morphological and structural parameters (inputs of the EWS) to mitigate coastal flooding impacts. This information can support the definition of adaptation strategies, which often involve the natural or artificial modification of these parameters. Sect. 2 presents the study area and the datasets, including offshore hydrodynamic observations and in situ- and video-derived topobathymetric data. Sect. 3 describes the process-based EWS used in this study and the methods adopted to generate synthetic storm events and beach profiles used in the sensitivity analysis. Sect. 4 presents the univariate 85 and multivariate analyses of the uncertainty in EWS predictions arising from physical boundary conditions. The main findings are then discussed, and conclusions are drawn.

2 Study area and datasets

2.1 Study area

The study area is Zarautz beach (Fig. 1), which is considered one of the sites on the Basque Coast with the highest hazard 90 due to storm events (Abalia et al., 2024) and significant interannual and storm-driven morphological variability (de Santiago



et al., 2021). This 2 km long sandy beach is flanked by two rocky headlands. It is divided into two distinct areas: the eastern part, which features a dune system and covers one-third of the beach, and the western part, which is backed by a concrete vertical seawall covering the remaining two-thirds. This section of the beach comprises several residential and commercial buildings that have suffered significant damage during storms. This has led to the deployment of the Zarautz Process-Based
 95 Early Warning System (ZPBEWS) in 2025 (Abalia, 2025) to help predict the severity, timing and affected areas of storms and identify appropriate mitigation measures.

The height of the seawall varies along the beach, gradually increasing from 4 m above mean sea level (MSL) in the west to 6 m in the east. The sediment grain size (d_{50}) is ≈ 0.31 mm (fine-medium sand; varying between 0.2 mm to 0.45 mm alongshore), with a beach slope of 0.02 (ranging from 0.02 to 0.06). The beach is characterized by a double sandbar system
 100 most of the time and evolves through all intermediate states (Wright and Short, 1984; de Santiago et al., 2013), being intermediate-dissipative in winter and intermediate-reflective in summer. The beach functions as an open beach with unconstrained circulation (Castelle and Coco, 2012; de Santiago et al., 2013), as the influence of the headlands is mainly concentrated at the lateral boundaries. During extreme events, the beach may exhibit transitional circulation (Castelle and
 105 Coco, 2012; de Santiago et al., 2013).

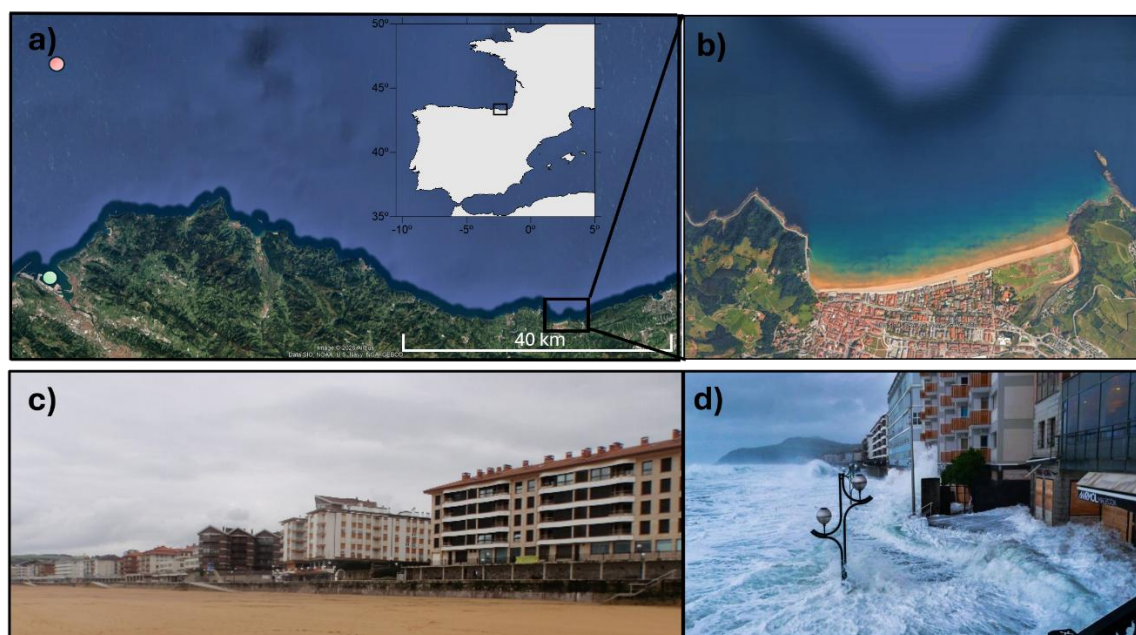


Figure 1: Study site. a) Location of Zarautz beach (Basque Coast). Source: "Image © 2026 Airbus Data. SIO, NOAA. U.S. Navy, NGA, GEBCO". b) The beach of Zarautz. Source: "Data SIO, NOAA. U.S. Navy, NGA, GEBCO". c) Engineered sector. d) Coastal flooding on the western sector of the beach. Credits: Asier @ranzadi. Red dot: Bilbao-Vizcaya wave buoy. Green dot: Bilbao 3 tidal gauge.



The offshore wave climate is dominated by a mean significant wave height (H_{s0}) of 1.5 m, a peak period (T_{p0}) of 10 s and a direction (θ_p) of 305°. Extreme wave conditions associated with a 10-year return period are characterized by an H_{s0} of 11 m and a T_{p0} of 20 s. The wave climate is seasonally variable, being winters (Dec-Mar) and summers (Jun-Sep) the most and less energetic seasons, respectively (González et al., 2004). The tidal regime is semi-diurnal. At spring (neap) tides, it is defined as high-mesotidal (low-mesotidal) (González et al., 2004). The storm surge can vary between -0.5 m and 1 m in the study area.

2.2 Offshore waves and tide data

Offshore wave conditions are measured hourly through the Bilbao-Vizcaya wave buoy (Fig. 1), moored over 600 m depth since 2004. During this measurement period, the wave climate exhibits a maximum H_{s0} of 13.7 m and T_{p0} of 24 s. The water level is measured through the Bilbao 3 tidal gauge (Fig. 1) since 1992 and referred to the MSL. The tidal regime varies from a maximum of 2.6 m to a minimum of -2.5 m. During neap tides, the minimum high tide value corresponds to 0.5 m.

2.3 Morphological and structural parameters

Zarautz beach is characterized by a beach profile with a double sandbar system. The scheme of morphological and structural parameters used in this study is represented in Fig. 2, which illustrates a typical profile of the urbanized section of the beach. The structural parameter refers to the seawall crest height (CH), which is defined as the level of the top of the promenade. Morphological parameters are divided into supratidal, intertidal and subtidal, depending on whether they are submerged or not. The supratidal zone is defined as the beach profile above the mean high tide elevation (HT). The toe crest distance (T_c) and the dry beach width (DBW) are the elevation and horizontal extent of the supratidal zone. The intertidal zone is defined as the beach profile between HT and the mean low tide elevation (LT). The intertidal zone extension depends on the foreshore slope (slp). The subtidal zone is defined as the beach profile below the LT. The distance to the innerbar (DI) and outerbar (DO), characterize the shape and distance of the subtidal zone sandbars.

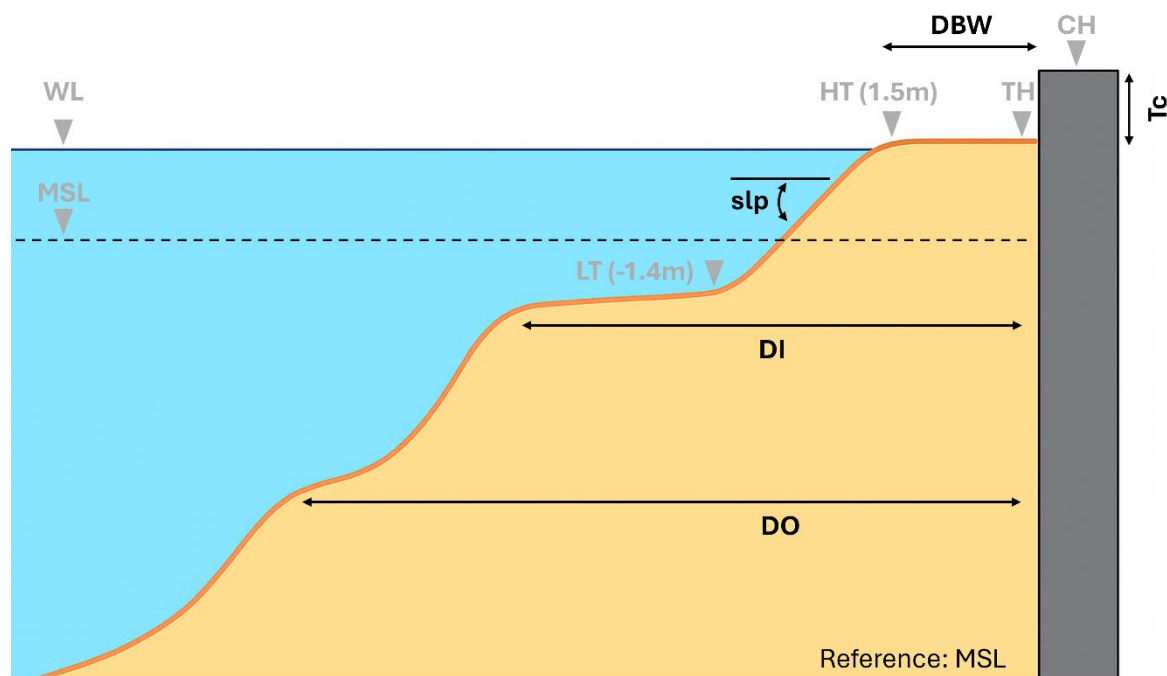


Figure 2: Representation of the beach profile parameters of the urbanized section of the beach of Zarautz. Seawall crest height (CH); toe crest distance (T_c); dry beach width (DBW); foreshore slope (slp); distance to the innerbar (DI); distance to the outerbar (DO).

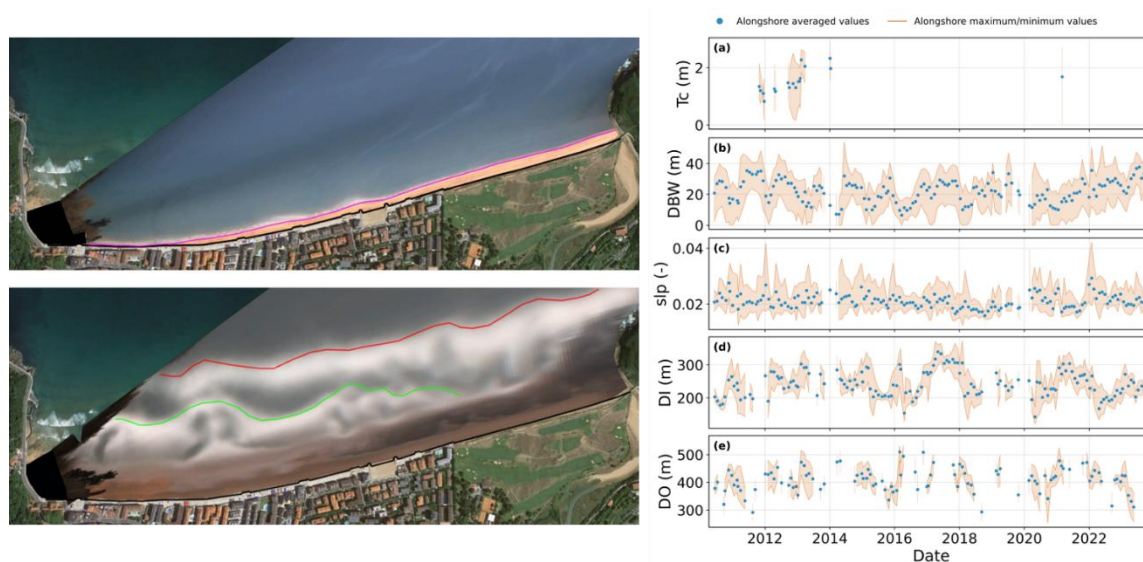
2.4 Topo-bathymetric data

Representative values of the morphological and structural parameters were derived primarily from coastal videometry observations, complemented by *in situ* surveys. The Zarautz videometry station, part of the Basque Videometry Network (Liria et al., 2021; <https://www.kostasystem.com/>), was used to derive shoreline and sandbar positions from monthly time-averaged orthorectified images (Fig. 3) acquired between 2010 and 2024 under low-energy conditions ($H_s < 2$ m) and fixed tidal levels. *In situ* measurements included RTK-GPS surveys of the supratidal and intertidal beach and coastal structures, together with multibeam echosounder surveys of the nearshore and subtidal bathymetry. Multiple topographic and topo-bathymetric surveys were collected between 2011 and 2021, making it possible to characterize the alongshore variability of the beach and promenade.

The evolution of the spatial distribution of morphological parameters on the urbanized sector of the beach is shown in Fig. 3. The T_c , obtained from *in situ* topobathymetric measurements, presents maximum, minimum and averaged values of 2.9 m, 0 m and 1.45 m, respectively. The other parameters, obtained through coastal videometry images, include DBW with values of 54 m, 0 m, and 22 m; slp with values of 0.042, 0.012, and 0.021; DI with values of 375 m, 120 m, and 240 m; and DO with values of 555 m, 255 m, and 410 m, respectively. Video estimations of morphological parameters were compared against in



situ measurements in concordant dates, providing mean (max) error of 0.3 m (0.7 m), 5 m (15 m), 0.006 (0.02), 20 m (48 m) and 35 m (98 m) for T_c , DBW, slp, DI and DO respectively. Regarding the structural data, the western zone of the beach presents a CH of 4 m, increasing to the east up to 6 m.



155 **Figure 3: Representation of morphological parameters. Left: extraction of shoreline and sandbar positions from time-averaged orthorectified images. Right: evolution from 2010 to 2024 along the urbanized part of the beach of Zarautz. Blue dot: Alongshore averaged values. Red lines: Alongshore maximum and minimum values.**

3 Methodology

160 The present study builds upon the Zarautz Process-Based Early Warning System (ZPBEWS), previously developed, calibrated, and validated against field observations by [Abalia \(2025\)](#). To assess the influence of the model's physical and structural input parameters on EWS predictions, the storm conditions and beach profiles considered in the different simulation scenarios are described in the following sections.

3.1 Description of the Zarautz process-based Early Warning System

165 The ZPBEWS was developed, calibrated and validated by [Abalia \(2025\)](#), achieving a match rate of 86% between predicted and observed alerts across 22 storm events. It specifically considers the influence of climatic and morphological parameters and dimensions of coastal defenses in the coastal flooding computations. The ZPBEWS consists of 3 modules ([Fig. 4](#)). Module 1 is composed of the Simulating Waves Nearshore (SWAN) spectral wave model ([Booij et al., 1997](#)) to simulate incident wave propagation from deep to intermediate water depth. Module 2 consists of the XBeach ([Roelvink et al., 2009a](#)) non-hydrostatic (XBNH) phase-resolving depth-averaged model (version 1.23.5983 known as XbeachX) used to compute



170 nearshore wave transformation and resulting overtopping processes in shallow foreshores. Module 3 uses a hazard scale to estimate the corresponding intensity of the simulated storm.

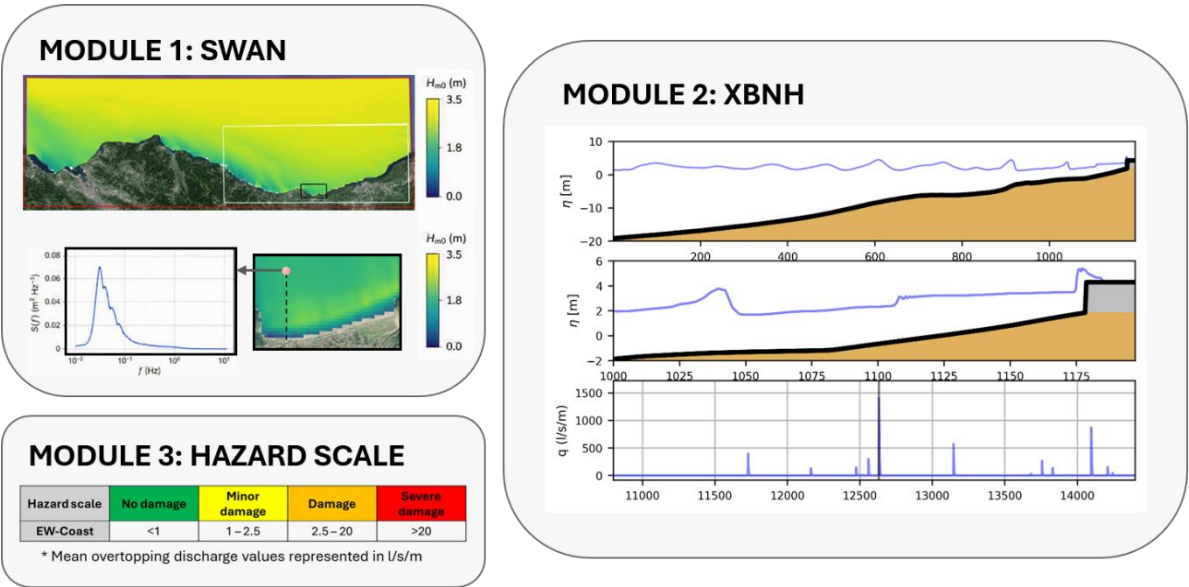


Figure 4: ZPBEWS workflow module by module.

The SWAN model (version 4131) is configured in 2D stationary mode with key physical processes such as white capping, wave breaking, bottom friction, and nonlinear quadruplet interactions enabled. To simulate the propagation of offshore wave energy density spectra from the Bilbao-Vizcaya wave buoy to the coast, three nested regular grids are used, progressively refining the representation of wave conditions from deep water (~580 m) to the shoreline. Bathymetric data for the model is sourced from [Eusko Jaurlaritza / Gobierno Vasco](#), and wave spectra and descriptive parameters are extracted at a depth of 19 meters off the coast of Zarautz.

The transformation of waves in the nearshore zone and the overtopping discharge characteristics is computed through the XBNH in 1D mode. The model is applied along the most exposed beach transect (Fig. 4; dashed line in Module 1; beach profile in 1D in Module 2) because it represents the worst-case scenario. The model is forced with non-hydrostatic incident wave time series derived from the SWAN spectra output at 19m depth using random phase seeding. A “wall” (reflective) condition is imposed at the land boundary. The number of layers is set to one since wave conditions in 19 m depth are weakly dispersive ($kh < 1$) for all the storm scenarios. Irregular mesh size is implemented in the cross-shore direction, varying from 4.5 m at the offshore boundary to 0.5 m at the shore. This allows to represent wavelengths with at least 30 points at the offshore boundary and 200 points at the toe of the seawall. The Courant–Friedrichs–Lewy (CFL) condition is set to 0.7. A Manning coefficient of $n=0.02 \text{ s/m}^{1/3}$ is adopted. The α model breaking parameter value and the minimum number of simulations required to minimize the influence of random phase seeding were calibrated to obtain the optimum performance



190 of the ZPBEWS in [Abalia \(2025\)](#). Instantaneous discharge values are computed from model results, velocity and water layer thickness, taken at the crest of the seawall every second. The mean overtopping discharge (q_x), widely used in coastal hazard classification, is calculated by integrating the instantaneous overtopping discharge time series over the test duration.

The warning level is computed through the most recent EW-Coast hazard level scale ([Garzon et al., 2023b](#)). It relates the magnitude of the computed mean overtopping discharge over an hour obtained in Module 2 with different warning levels for
195 urban components and buildings ([Fig. 4](#), Module 3), ranging from: i) Level 1: No damage (green), ii) Level 2: Minor damage (yellow), iii) Level 3: Damage (orange), iv) Level 4: Severe damage (red).

3.2 Determination of synthetic events

Synthetic events are defined within the hydrodynamic dataset to minimize the number of study cases considered, as simulating all possible scenarios is impractical. First, the offshore hydrodynamic dataset was filtered to retain only the
200 potentially hazardous cases identified by the Basque Maritime Coastal Flooding Early Warning System (BMCEWS) ([Gaztelumendi et al., 2016](#)). The BMCEWS is a deterministic EWS based on a calibrated empirical formulation that directly relates the storm conditions (H_{s0} , T_{p0} and WL) to the measurements of economic amount of damage over the entire Basque Coast over 10 years period. These potentially hazardous events, totalling around 1500 cases, consist of combinations of H_{s0} , T_{p0} and WL ([Fig. 5](#), red dots). The range of values varies from a maximum H_{s0} of 11.6 m, T_{p0} of 24 s and WL of 2.6 m to a
205 minimum H_{s0} of 1 m, T_{p0} of 9 s and WL of -0.25 m. The wide range of values indicates that hazardous conditions are not necessarily linked to extreme values of H_{s0} , T_{p0} and WL taken in isolation. Indeed, potentially hazardous events can also occur when some variables are relatively low, due to their combined effect.

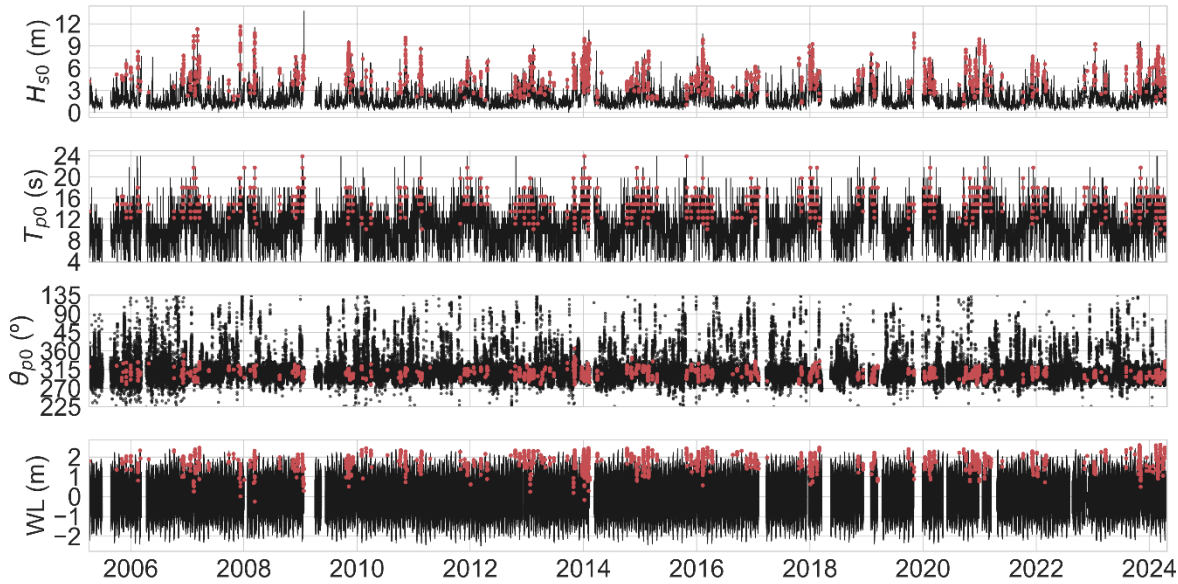


Figure 5: Evolution over time of hydrodynamic characteristics of the potentially hazardous events represented through red dots.

The offshore conditions of potentially hazardous events are then propagated using the SWAN wave model to a water depth of 19 meters offshore of Zarautz beach. This provides the nearshore wave characteristics of potentially hazardous events (H_{si} , T_{pi} and WL) which are subsequently used to define the set of synthetic events. The 99.75th and 5th percentiles are chosen as upper and lower bounds of the range, respectively, with "n" intermediate values defined between them. The minimum WL value is adjusted to match the lowest high tide peak ever recorded. The H_{si} values are 1.5, 3, 4.5, 6 and 7 m. The T_{pi} values are 11, 17.5 and 24 s. The WL values are 0.5, 1, 1.5, 2, 2.25 and 2.5 m. The nearshore wave peak direction (θ_{pi}) is reduced to a single representative value of 345° (perpendicular to the coast) as it shows minimal variability (330°-360°). This leads to a total of 90 synthetic events (Table 1).

3.3 Determination of synthetic cross-shore beach profiles

Synthetic cross-shore beach profiles are constructed from the morphological dataset to limit the number of study cases, as simulating all possible morphological configurations is not feasible. The crest height (CH) was fixed at 4 m above MSL, corresponding to the most exposed beach transect, located in its western section (Fig. 4; dashed line in Module 1). For the other parameters defining the morphological characteristics of the beach profile (Fig. 2), the values corresponding to the 98th and 2nd percentiles were used. This gives 0.8 and 2.5 m for T_c , 0 and 40m for DBW, 0.0175 and 0.0325° for slp, 210 and 330 m for DI, and 370 and 520 m for DO covering the boundaries of the data space (Table 1).

The workflow used to generate synthetic cross-shore beach profiles developed in Abalia (2025) is summarized in Fig. 6. First, the promenade elevation is set to CH (p1), and the beach profile is initiated at CH – T_c (p2). The synthetic profile is



then constructed through successive linear segments: (i) a horizontal extension of length DBW from p2 to p3, (ii) a segment with slope slp from p3 to p4, and (iii) a segment from p4 to p5 whose slope is parameterized by a linear function (Fig. 6, red arrow). From p5 seaward to the depth of closure, the synthetic profile is completed by appending a measured segment (hereafter MDC profile) representative of a well-developed outer bar, derived from the 2021 topo-bathymetric survey. The MDC profile allows for cross-shore outer-bar migration (shoreward–seaward) over a distance (DO – DI) along the direction of the mean slope.

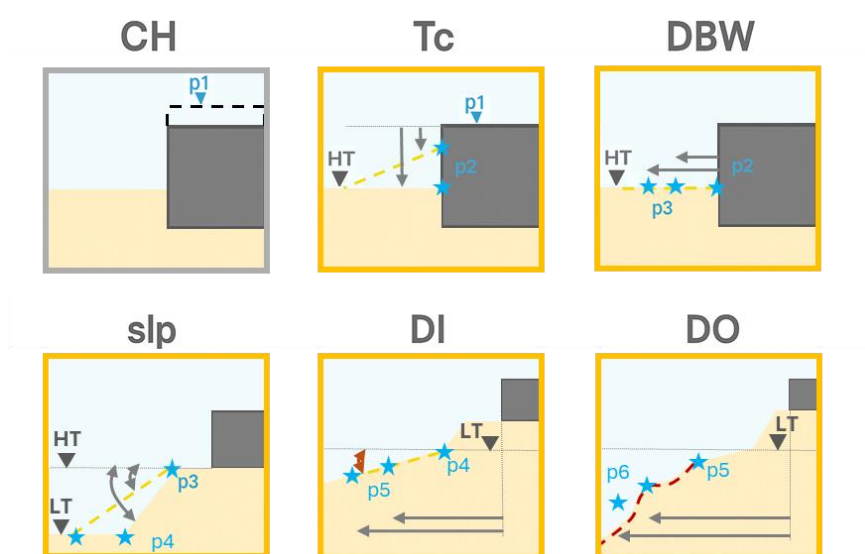


Figure 6: Coupling sequence of morphological parameters for the synthetic profiles generation. Orange line: parametric profile. Blue symbols: points defined by morphological parameter values. Red lines: Unknown values. Acronyms defined in Fig 2.

By incorporating the values of the representative morphological parameters (Table 1) into the proposed parametric framework (Fig. 6), it is possible to generate a database of 32 synthetic profiles (Fig. 7), representative of Zarautz beach profile, an intermediate dissipative beach (de Santiago et al., 2013).



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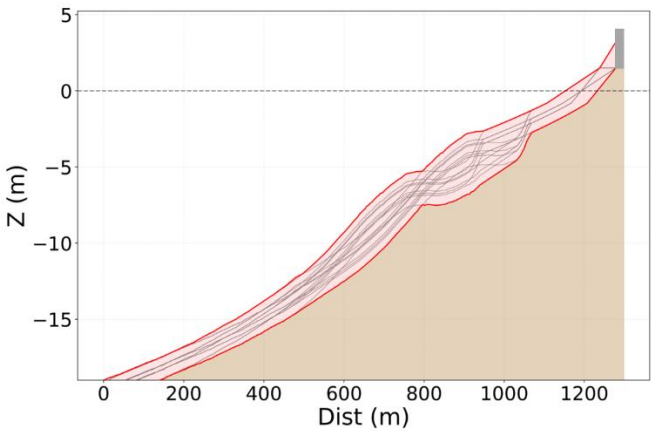


Figure 7: Representation of synthetic profiles database.

3.4 Scenarios simulated with the ZPBEWS

The synthetic hydrodynamic (90) and morphological (32) cases that cover the variability of the dataset are set as physical boundary conditions (hereinafter referred to as PBC) for the ZPBEWS. The CH and WL parameters are combined to generate the seawall freeboard (R_c) parameter that represents the vertical distance between the water level elevation and the crest of the structure. Hydrodynamic PBC are defined as H_{si} , T_{pi} and R_c , and morphological PBC are defined as supratidal and intertidal (hereinafter referred as supratidal), DBW, T_c and slp and subtidal, DI and DO. The values of the parameters used as PBC are represented in Table 1, with a total of 2880 simulations considering all possible combinations.

Table 1: Morphological, hydrodynamic and structural parameters used for the ZPBEWS physical boundary conditions. Seawall crest height (CH); toe crest distance (T_c); dry beach width (DBW); foreshore slope (slp); distance to the innerbar (DI); distance to the outerbar (DO); nearshore significant wave height (H_{si}), peak period (T_{pi}); seawall freeboard (R_c).

	Min	Max	n
Morphological			
<u>Supratidal and intertidal</u>			
DBW [m]	0	40	2
T_c [m]	0.8	2.5	2
Slp	0.0175	0.0325	2
<u>Subtidal</u>			
DI [m]	210	330	2
DO [m]	370	520	2
Hydrodynamic & structural			



H_{si} [m]	1.5	7	5
T_{pi} [s]	11	24	3
WL [m]	0.5	2.5	6
R_c [m]	1.5	3.5	6

4 Results

255 4.1 Univariate uncertainty analysis of hazard level predictions

The influence of the physical boundary conditions (PBC) on the predicted hazard level (HL, HL = 1 (no damage), 2 (minor damage), 3 (damage) or 4 (severe damage)) was evaluated using the 2880 simulations generated from the combination of synthetic storms and beach profiles. The uncertainty associated with each PBC (ΔHL_p), was quantified as the variation in the predicted HL resulting from changes in the corresponding PBC value, defined as:

$$260 \quad \Delta HL_p = \text{diff}(HL_{pn}, HL_{pm}) \quad (1)$$

where p denotes the PBC under investigation, and n and m correspond to its minimum and maximum values, respectively. Negative values of ΔHL_p indicate that the hazard level increases with increasing values of the corresponding PBC, whereas positive values indicate that the hazard level decreases as the PBC increases ($\Delta HL_p \in \{-3, \dots, 3\}$). Because the PBC values are discretized, ΔHL_p can be computed as a series of pairwise differences in the predicted hazard levels associated with the range
 265 of values considered for each PBC.

A univariate sensitivity analysis was performed to isolate the contribution of each PBC to the uncertainty in the predicted HL. Each PBC was varied independently while remaining variables were held constant. The resulting distributions of ΔHL_p are presented in Fig. 8. Among the hydrodynamic PBCs, variations in seawall freeboard (R_c), nearshore significant wave height (H_{si}) and peak wave period (T_{pi}) resulted in differences of up to three HL (i.e., from *no damage* to *severe damage*) in
 270 approximately 60%, 40%, and 0.1% of the simulations, respectively. For the morphological PBCs, variations in beach slope (slp), dry beach width (DBW), distance to the innerbar (DI), toe crest distance (T_c), and distance to the outerbar (DO) produced differences of up to two hazard levels (i.e., from *no damage* to *damage* or from *minor damage* to *severe damage*) in approximately 3%, 5%, 1%, 1%, and 0.2% of the simulations, respectively. Overall, these results indicate that the uncertainty in the predicted hazard level is primarily controlled by the hydrodynamic PBCs, followed by the supratidal
 275 morphological variables, whereas the subtidal morphological variables have a comparatively smaller influence. Furthermore, the predicted HL increases with increasing H_{si} , T_{pi} , slp, and DO, whereas it decreases with increasing R_c , T_c , DBW and DI.

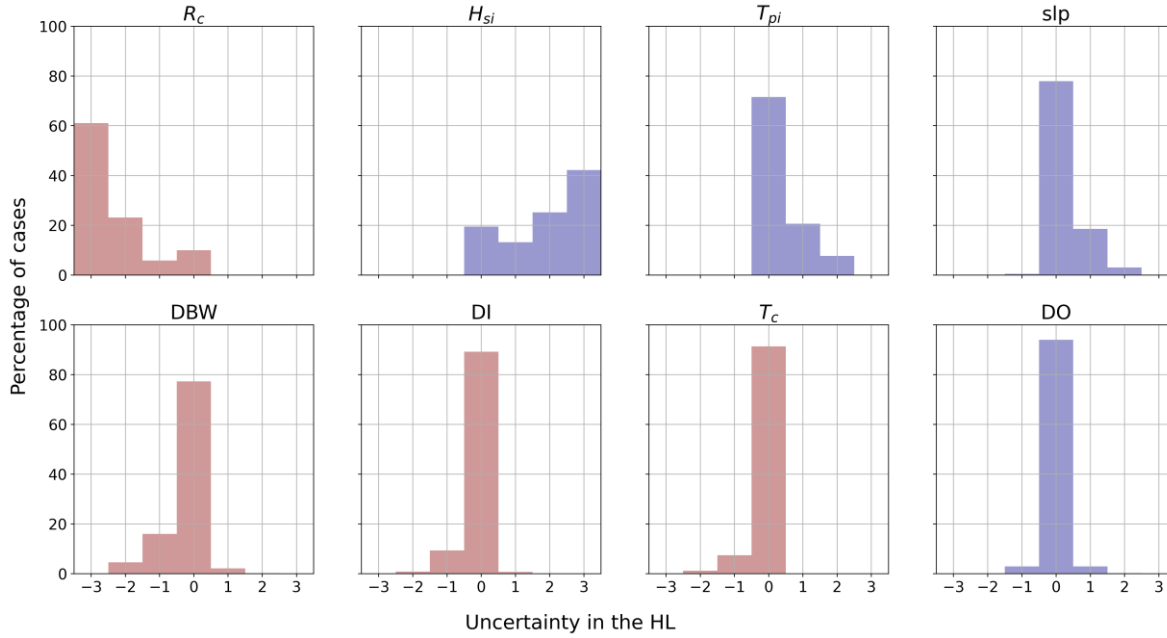


Figure 8: Percentage of occurrence of ΔHL (uncertainty in the Hazard Level HL) for different PBC parameters (see Table 1 for the acronym definition). Red: Inverse relation. Blue: Direct relation.

280 The magnitude of the uncertainty associated with a given PBC variability is not necessarily independent of the values adopted by the other PBCs. For instance, the uncertainty induced by variations in the R_c on the predicted hazard level may depend on the H_{si} conditions. Consequently, the contribution of an individual PBC variability to the uncertainty in HL predictions cannot always be assessed independently highlighting a limitation of the univariate approach. To account for the combined effects of multiple PBCs, a multivariate analysis is conducted in Sect. 4.2 to assess the interactions between PBCs and provide a more comprehensive evaluation of their influence on HL predictions.

4.2 Multivariate uncertainty analysis of hazard level predictions

To account for the interactions between PBCs, a multivariate analysis was performed by computing the uncertainty induced by each PBC in the predicted HL (ΔHL_p , Eq. 1) for specific combinations of the remaining PBCs. Unlike univariate analysis, which isolates the influence of each variable, this approach evaluates how the uncertainty associated with a given PBC depends on the prevailing hydrodynamic and morphological conditions.

The univariate results demonstrated that the uncertainty in hazard level predictions is primarily driven by the hydrodynamic PBCs. Consequently, the multivariate analysis focuses on quantifying the influence of the morphological PBCs under different hydrodynamic forcing conditions. To this end, the simulation database was partitioned into subsets defined by

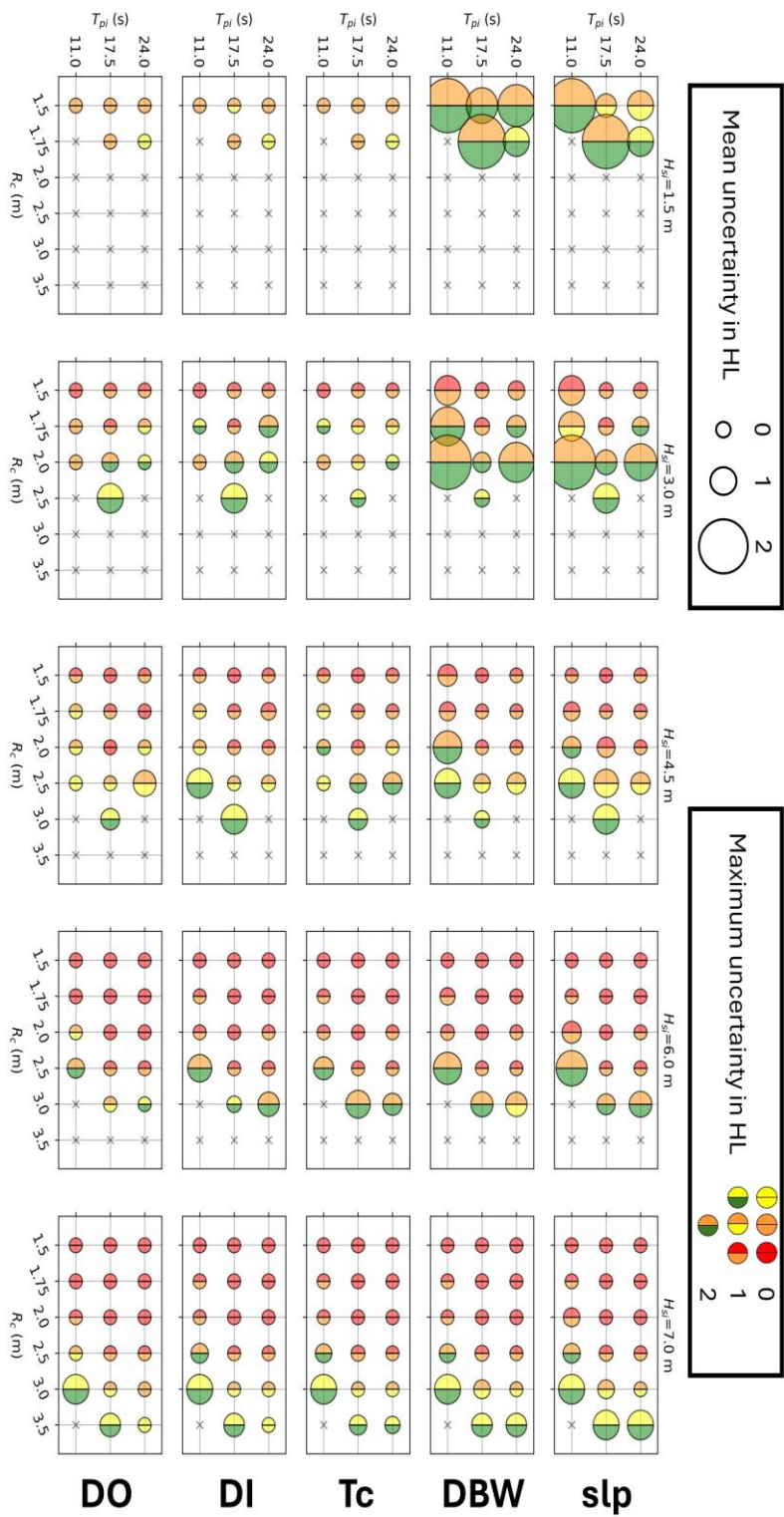


combinations of H_{si} , R_c , and T_{pi} . For each hydrodynamic subset, the uncertainty associated with each morphological PBC
295 was evaluated independently (Fig. 9).

In Fig. 9 each circle represents the uncertainty in the predicted HL induced by a specific morphological PBC for a given
combination of H_{si} , R_c and T_{pi} . The color gradient within each circle illustrates the range of predicted hazard levels, with the
highest and lowest hazard levels displayed on the left and right halves of the circle, respectively. Circle size is proportional to
the mean uncertainty (mean ΔHL_p), whereas the difference in the color gradient (green–yellow–orange–red) indicates the
300 maximum uncertainty observed. The absence of a circle denotes hydrodynamic conditions for which no hazard is predicted.

The results reveal that hazard occurrence is primarily controlled by the hydrodynamic forcing. No hazard is predicted under
combinations of low H_{si} and T_{pi} together with high R_c values. In particular, severe damage ($HL = 4$) is never predicted for the
lowest wave height condition ($H_{si} = 1.5$ m), irrespective of the remaining PBCs, and hazards only occur when combined with
the lowest R_c values. Likewise, high R_c values of 3.0 and 3.5 m prevent the occurrence of severe damage ($HL = 4$) under all
305 hydrodynamic scenarios considered.

The influence of the morphological PBCs varies substantially depending on the studied hydrodynamic conditions. Slp and
DBW consistently induce greater uncertainty than T_c , DI, and DO particularly under low-to-moderate wave energy
conditions ($H_{si} = 1.5$ – 4.5 m). As wave height increases ($H_{si} = 4.5$ – 7.0 m), the uncertainty associated with these morphological
variables progressively decreases, suggesting that extreme hydrodynamic forcing dominates the predicted hazard level and
310 reduces the relative influence of beach morphology. Conversely, under high R_c conditions, the contribution of the
morphological PBCs to the overall prediction uncertainty becomes comparatively more important to low R_c conditions,
indicating that morphological characteristics exert a stronger control on hazard predictions when the protective effect of the
coastal structure limits overtopping.





315 **Figure 9: Maximum and mean uncertainty in the HL predictions induced by each morphological PBC under different hydrodynamic conditions. Plot rows: morphological PBC. Plot columns: H_{si} . x axis: R_c . y axis: T_{pi} . Circle color gradient: maximum uncertainty. Circle size: mean uncertainty. Crosses: absence of hazard.**

5 Discussion

5.1 Determination of physical boundary conditions

320 The use of representative synthetic storm events and beach profiles was motivated by the need to achieve a balance between computational efficiency and an adequate representation of the range of environmental conditions. Simulating all possible combinations of hydrodynamic and morphological conditions would result in a prohibitively large number of numerical simulations. Therefore, only a reduced set of representative cases was selected to span the observed variability of the input parameters while preserving the physical consistency of the dataset.

325 Several statistical techniques have been proposed to reduce large datasets into a limited number of representative conditions, including copula-based sampling (Plomaritis et al., 2018; Jäger and Nápoles, 2017), K-means algorithm (MacQueen, 1967) or Maximum Dissimilarity Algorithm (MDA) (Camus et al., 2011). These methods are particularly well suited for identifying representative combinations within large multivariate datasets. In the present study, however, a percentile-based sampling strategy was adopted. This approach provides a straightforward and transparent framework for defining
 330 representative conditions with clearly identifiable statistical boundaries while ensuring that the selected combinations remain consistent with the joint distribution of the physical variables. The objective was not to reproduce the full statistical distribution of storm events or beach morphologies, but rather to characterize the sensitivity of hazard predictions across the range of conditions that are typically encountered over interannual timescales. For hydrodynamic forcing, representative values were selected between the 5th and 99.75th percentiles to provide a sufficiently dense sampling of the dataset. In
 335 contrast, for beach morphology only the 2nd and 98th percentiles of each morphological parameter were considered, as introducing additional intermediate values would have considerably increased the number of simulations while providing limited additional information to the sensitivity analysis. The adopted sampling strategy therefore represents a pragmatical compromise between computational cost and the ability to characterize the influence of both hydrodynamic and morphological boundary conditions on hazard level predictions.

340 5.2 Influence of physical boundary conditions on hazard level prediction

Studies specifically addressing the influence of physical boundary conditions (PBCs) on the uncertainty of EWS predictions remain scarce and are essentially limited to the recent works of de Santiago et al. (2023) and Garzon et al. (2023a). Consequently, the interpretation of the present results also relies on studies investigating the sensitivity of process-based numerical models to hydrodynamic and morphological variability through more conventional coastal flooding indicators,



345 such as TWL (Cohn and Ruggiero, 2016; Toimil et al., 2023), wave overtopping volumes (Phillips et al., 2017) and flooded area (Cueto Fonseca et al., 2021; Toimil et al., 2023).

The present analysis shows that the predicted hazard level (HL) increases with increasing significant wave height (H_s), peak wave period (T_p), beach slope (slp), and distance to the outerbar (DO), whereas it decreases with increasing seawall freeboard (R_c), toe crest distance (T_c), dry beach width (DBW), and distance to the innerbar (DI). These trends are physically
 350 consistent with the established understanding of coastal flooding processes. In particular, the positive relationship between slp and HL agrees with the findings of Cohn and Ruggiero (2016), who identified slp as one of the primary controls on TWL. Likewise, widely used empirical formulations for wave runup and overtopping (Stockdon et al., 2006; Mase et al., 2013; Van der Meer et al., 2016; Gomés et al., 2018) predict increasing flooding intensity with increasing H_s , T_p , WL, and slp, in agreement with observations reported by Almeida et al. (2013) and Silveira et al. (2016).

355 The influence of coastal erosion on flooding hazard is less straightforward. Previous studies have reported contrasting responses: Phillips et al. (2017) and Cueto Fonseca et al. (2021) found that short-term erosion tends to increase overtopping, whereas Toimil et al. (2023) and Garzon et al. (2023a) reported the opposite effect. These apparent discrepancies likely arise because erosion is not a unique morphological process but rather the combined expression of multiple morphological changes (Gomés et al., 2020). Shoreline retreat, dune lowering, berm narrowing, beach steepening, or modifications of the
 360 nearshore profile may occur simultaneously, with some processes enhancing wave overtopping while others reduce it. The present results support this interpretation by showing that individual morphological parameters can have opposite effects on hazard predictions. Consequently, the overall impact of erosion depends on the relative magnitude of the morphological changes affecting the supratidal and subtidal zones, which complicates direct comparisons among studies. This is particularly relevant along the Basque coast, where beach responses to storms depend on local morphology and exposure conditions (de
 365 Santiago et al., 2021, Abalia et al., 2024).

The sensitivity analysis further demonstrates that uncertainty in HL predictions is predominantly controlled by hydrodynamic boundary conditions, which can modify the predicted hazard by up to three levels, whereas morphological boundary conditions induce a maximum variation of two HL. Among the morphological variables, supratidal parameters exert a substantially stronger influence than subtidal parameters. These findings are consistent with previous studies showing
 370 that hydrodynamic forcing is the dominant source of uncertainty in coastal flood forecasts. Garzon et al. (2023a), for example, reported that hydrodynamic variability produced changes of up to two HL, whereas supratidal erosion modified the predicted hazard by no more than one level. Similarly, de Santiago et al. (2023) concluded that hydrodynamic variability exerts a greater influence on hazard predictions than changes in subtidal morphology. The larger uncertainty obtained in the present study is most likely explained by the broader range of hydrodynamic and morphological conditions explored. More
 375 generally, the results reinforce the conclusions of Cohn and Ruggiero (2016), who identified supratidal and intertidal morphology as more influential than subtidal morphology in controlling the uncertainty of coastal flooding indicators.



A key outcome of this work is that the influence of morphology is itself conditioned by the hydrodynamic forcing. Under energetic wave conditions or low seawall freeboard, hazard predictions become relatively insensitive to morphological variability because overtopping processes are primarily governed by the incoming wave energy. Conversely, under low-to-moderate forcing conditions, relatively small changes in beach morphology may determine whether critical overtopping thresholds are exceeded, thereby exerting a much stronger influence on the predicted HL. This result is consistent with [de Santiago et al. \(2023\)](#), who reported that differences in beach-profile shape affected hazard-level forecasts, particularly for storms of intermediate intensity. The present analysis extends those findings by demonstrating that the influence of morphology depends strongly on the prevailing hydrodynamic conditions. This result suggests that frequent morphological updates may not be essential for maintaining reliable EWS predictions during extreme storm events but become considerably more important for forecasting low-to-moderate events, which often occur more frequently and constitute most operational forecast activity.

Finally, the larger uncertainty observed under low-to-moderate energy and high-freeboard conditions can also be explained by the threshold-based definition of the hazard scale adopted in the EWS. At low hazard levels, relatively small variations in overtopping discharge may cause transitions between hazard classes, making the forecasts particularly sensitive to uncertainties in the physical boundary conditions. In contrast, under extreme hydrodynamic forcing, overtopping rapidly exceeds the highest hazard thresholds, producing a saturation effect whereby additional changes in the physical conditions have little influence on the predicted hazard level. This behavior highlights that the uncertainty of categorical hazard forecasts is controlled not only by the underlying physical processes but also by the definition of the hazard classification itself.

5.3 Operational implications of real-time acquisition errors for EWS performance

The Zarautz Process-Based Early Warning System (ZPBEWS) is designed to provide hazard forecasts up to 72 h in advance of storm impacts. In its operational configuration, offshore wave and water-level forecasts are retrieved from the Copernicus Marine Iberia–Biscay–Ireland (IBI) (data.marine.copernicus.eu) forecasting system, whereas the beach morphology is reconstructed in near real time from coastal video imagery using the profile generation methodology developed in this study. Consequently, both hydrodynamic and morphological boundary conditions are affected by measurement and forecasting errors that inevitably propagate into the predicted hazard levels.

To complement the sensitivity analysis presented in the previous sections, an additional assessment was performed to quantify the effect of realistic acquisition errors on operational EWS predictions. A base scenario was first defined using the twelve most significant offshore storms recorded between 2010 and 2020, as identified from the flood warnings issued by the Euskalmet Basque Meteorological Agency ([Table 2](#)). These storms were simulated over a representative winter beach profile derived from monthly morphological observations obtained from the Zarautz coastal video monitoring system between 2010



and 2024 (Fig. 3). The base profile corresponds to the mean winter morphology (December to February) and represents the beach configuration most frequently encountered during the storm season.

410 **Table 2: Measured H_{s0} , T_{p0} , θ_{p0} , WL and hazard level for Euskalmet Basque Meteorological Agency coastal-flooding warnings.**

Event date	H_{s0}	T_{p0}	θ_{p0}	WL	Hazard level
9/11/2010	9.3	14.2	315	2.27	Level 4
14/12/2011	6.5	12.5	310	1.7	Level 2
7/1/2014	7.7	18	295	1.43	Level 3
28/1/2014	7.9	15.4	304	1.6	Level 3
2/2/2014	8.55	19.9	309	2.35	Level 4
24/2/2015	7.8	13.3	317	1.64	Level 3
27/10/2015	3.3	14.3	297	2.43	Level 2
3/1/2018	3.2	12.5	298	2.15	Level 2
4/1/2018	7.1	18.2	304	2.2	Level 3
18/1/2018	6.7	16.6	307	1.65	Level 3
23/1/2019	6.1	13.4	319	2.25	Level 3
3/10/2020	7.6	11.8	305	2.1	Level 3

The error of hydrodynamic forecast was estimated by comparing historical Copernicus forecasts with observations from the Bilbao–Vizcaya wave buoy and the Bilbao3 tide gauge over the 2022–2026 period for potentially hazardous events identified using the BMCEWS criteria (Sect. 3.2). Mean (maximum) absolute errors of 0.5 m (2.3 m), 2 s (6 s), and 0.074 m (0.26 m) were obtained for H_{s0} , T_{p0} , and WL, respectively. Similarly, the uncertainty associated with the real-time reconstruction of beach morphology was quantified by comparing video-derived morphological parameters with field measurements, yielding mean (maximum) errors of 0.3 m (0.7 m), 5 m (15 m), 0.006 (0.02), 20 m (48 m), and 35 m (98 m) for T_c , DBW, slp, DI, and DO, respectively.

The hazard predictions obtained for the base scenario were subsequently compared with those generated after introducing representative acquisition errors into the hydrodynamic and morphological boundary conditions. The positive (negative) scenarios correspond to the most (least) conservative operational configuration, combining increases (decreases) in H_{s0} , T_{p0} , WL, slp, and DO with decreases (increases) in T_c , DBW, and DI, thereby maximizing (minimizing) the expected hazard level.

The results (Fig. 10) indicate that operational errors affecting the hydrodynamic forcing generally have a larger impact on hazard predictions than uncertainties associated with beach morphology. Extreme errors in wave forecasts may lead to substantial changes in the predicted hazard, confirming that the reliability of offshore forecasts remains a critical requirement



for operational coastal early warning systems. Nevertheless, when considering the average acquisition errors representative of routine operational conditions, hydrodynamic boundary conditions exert slightly higher uncertainties than morphological boundary conditions, therefore producing comparable variations in the predicted hazard level. This finding suggests that improvements in real-time beach monitoring may provide benefits comparable to those obtained from incremental improvements in wave forecasting accuracy.

A more detailed analysis reveals that uncertainty in the peak wave period is the dominant contributor among the hydrodynamic variables, whereas beach slope is the morphological parameter exerting the greatest influence on forecast uncertainty. Regarding beach morphology, these findings are consistent with the sensitivity analysis presented in the previous sections, which identified beach slope as one of the primary controls on hazard level variability. In contrast, the results for hydrodynamic forcing indicate a different behavior: although peak wave period was found to be the least influential variable when considering the full range of variability, it becomes the dominant source of uncertainty under operational conditions. This shift is primarily attributable to the relatively large acquisition and forecasting discrepancies associated to peak wave period. This discrepancy usually relays in errors in the prediction of the arrival time of swells or the presence of bimodal sea states.

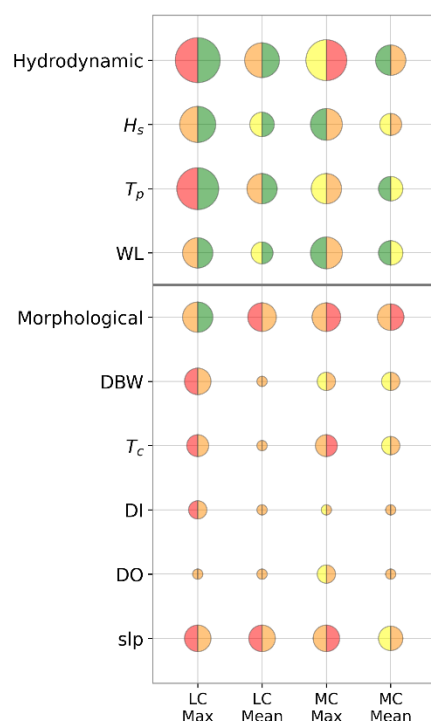


Figure 10: Maximum and mean uncertainty in the HL predictions induced by the acquisition errors in hydrodynamic and morphological PBC. MC: Most conservative. LC: Least conservative. Circle color gradient: maximum uncertainty. Circle size: mean uncertainty.



445 From an operational perspective, these findings highlight that the relative importance of hydrodynamic and morphological
uncertainties depends on the magnitude of the acquisition errors considered. While reducing errors in offshore wave
forecasts remains the primary objective for improving forecast reliability considering extreme errors, investing in accurate,
automated morphological monitoring is equally justified for operational EWSs. Indeed, under the mean and most common
acquisition errors that constitute the majority of operational forecasts, relatively small errors in beach morphology may alter
450 the predicted hazard and consequently influence warning issuance and emergency management decisions.

6 Conclusion

This study investigated the uncertainty induced by physical boundary conditions on the hazard predictions of the developed
Zarautz Process-Based Early Warning System (ZPBEWS). Beyond quantifying the influence of hydrodynamic and
morphological variability on forecasted hazard levels, the analysis also assessed the impact of realistic acquisition errors
455 associated with the operational implementation of the system.

The results demonstrate that uncertainty in hazard predictions is primarily controlled by the hydrodynamic boundary
conditions. Variations in offshore wave characteristics and seawall crest freeboard may produce changes of up to three
hazard levels, whereas morphological boundary conditions generate a lower, although still significant, uncertainty of up to
two hazard levels. Among the morphological variables, supratidal parameters, particularly beach slope and dry beach width,
460 have a considerably greater influence on hazard predictions than subtidal characteristics.

A key finding of this work is that the influence of morphology is strongly conditioned by the hydrodynamic forcing. Under
energetic wave conditions or low-freeboard configurations, hazard predictions become largely insensitive to morphological
variability because overtopping is dominated by the incoming wave energy. Conversely, under higher freeboard values, both
supratidal and, to a lesser extent, subtidal morphology exerts greater control on hazard classification. Considering low-to-
465 moderate storm conditions, supratidal morphology becomes more influential. These results provide a physical explanation
for the contrasting conclusions reported in previous studies regarding the role of beach morphology in coastal flooding and
demonstrate that its influence should be studied on a parameter-specific basis and cannot be evaluated independently of the
hydrodynamic regime.

The operational analysis further shows that realistic average acquisition errors in hydrodynamic and morphological inputs
470 produce comparable levels of uncertainty, whereas extreme acquisition errors in hydrodynamic forcing produce a
substantially larger impact in the forecasted hazard than those arising from morphological inputs. This finding highlight that,
although improving offshore wave forecasts remains essential for reliable early warning systems, accurate real-time
morphological observations can also significantly improve forecast robustness, particularly under moderate conditions.



Overall, this study provides the first comprehensive assessment of the respective contributions of hydrodynamic variability, morphological variability, and operational acquisition errors to the uncertainty of a process-based EWS. Beyond improving the understanding of the physical controls governing forecast uncertainty, the results provide practical guidance for the operational design of coastal early warning systems. In particular, the results suggest that the frequency and zones of beach morphology updates could be adapted to the expected storm severity, allowing monitoring resources to be allocated more efficiently while maintaining forecast reliability. More broadly, the proposed methodology offers a transferable framework for evaluating uncertainty and optimizing monitoring strategies in process-based coastal early warning systems deployed at other sites.

Code and data availability

The authors do not have permission to share data.

Author contributions

Aritz Abalia: Conceptualization, Methodology, Formal analysis, Data curation, original draft preparation, Writing - Review & Editing. **Iñaki de Santiago:** Conceptualization, Methodology, Formal analysis, Writing - Review & Editing. **Pedro Liria:** Conceptualization, Data curation, Formal analysis, Review. **Roland Garnier:** Conceptualization, Formal analysis, Review. **Iratí Epelde:** Data curation, Formal analysis, Review. **Asier Nieto:** Data curation, Formal analysis, Review. **Denis Morichon:** Conceptualization, Methodology, Formal analysis, Writing - Review & Editing.

Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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