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Coastal flood risk management: a decision-aid system using real-time observations and high-resolution nearshore wave modeling – Applications to the Biarritz coastline

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Abstract:

Coastal flooding and wave overtopping along densely urbanized coastlines poses a major threat to both communities and property, a threat that is projected to increase with climate change. Therefore, efficient early-warning and decision-aid systems are crucial for enhancing coastal zone management and public safety. The approach examined in this study uses a unique combination of continuous observation and a high-resolution, operational, hydrodynamic modeling suite to support coastal flood risk management at a highly local scale. The modeling suite includes complementary approaches that consider both spectral and phase-resolving computations. A conclusive model-data comparison is presented, utilizing two complementary datasets under real conditions at the Grande Plage of Biarritz (SW France): (i) intensive wave and runup field measurements collected during a representative storm event and (ii) a multi-year historical database of storm impact indicators derived from coastal videometry. Monitoring and modeling components are integrated into an operational decision-support system, which empowers the Biarritz municipality to implement timely protection actions against storm impacts. The effectiveness of this strategy is demonstrated for the case of the extreme storm event Justine in January 2021.

Keywords:

Coastal flooding, Early Warning System, Videometry, Wave modeling, Biarritz.

1. Introduction

Coastal flooding poses a growing threat to densely populated urbanized areas, which is expected to further increase with the sea level rise induced by global warming. Inadequate defenses leave many urban seafronts vulnerable to wave overtopping during severe storms, despite occasional temporary countermeasures. In this context, Early Warning Systems (EWS) are crucial for protection strategies deployable by local authorities (GARZON *et al*., 2023). However, the accurate prediction of storm impacts, particularly of local wave runup contributions, remains a key challenge (GALLIEN, 2016; FIEDLER *et al*., 2020). This study proposes an innovative approach through integration of real-time observations and high-resolution hydrodynamic modeling to reinforce a beach-scale EWS and decision-support solution, empowering local authorities to implement early protective countermeasures.

2. Materials and methods

2.1 Study site

This study focuses on the coastal domain around Biarritz municipality in the south-west of France (Figure 1). At the heart of the city, the iconic *Grande Plage* of Biarritz (GPB) is an urban embayed beach. It is topped by a protective sea wall, which defines a promenade backed by the city's seafront landmarks, including the Casino and the *Hôtel du Palais*. The landward area of the GPB faces recurrent coastal flooding, especially during winter, in the form of extreme wave runup that overtops the sea wall, flood the promenade, and impact nearby infrastructures.

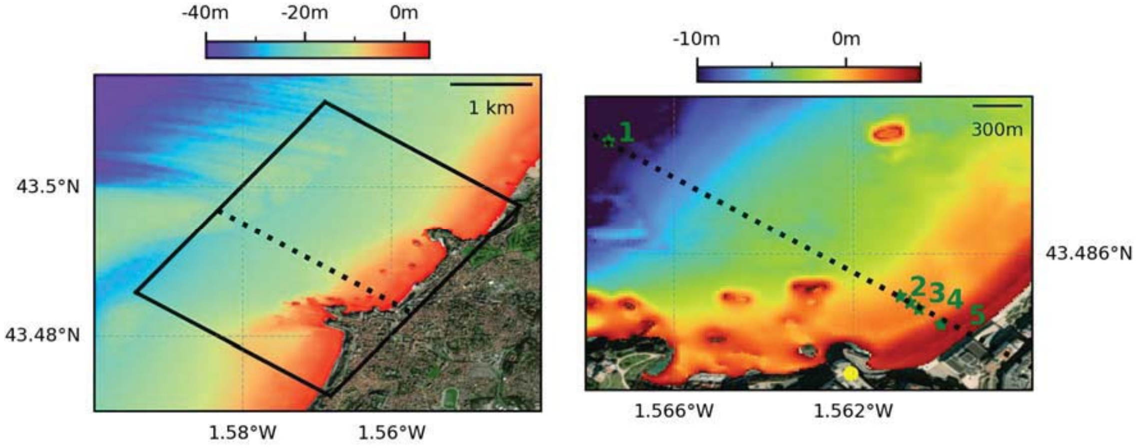

Figure 1. (Left) Study area: bathymetry relative to chart datum (color scales), with solid black lines marking the limits of the phase-resolving model domain; and dashed line indicating a cross-shore transect of interest. (Right) Zoom on the nearshore area, with in situ sensor positions in green and video station location in yellow.

The sea wall height is about 1.5 m with a mean crest elevation of 7.65 m above chart datum. The sandy beach profile is intermediate-reflective with a flat low-tide terrace (slope ~2-3%) and a steep foreshore (slope 8-10%) (PINAULT *et al.,* 2022). The GPB area is mesotidal with a 4.5 m spring tidal range. The beach is exposed to energetic W-NW swells with a 10-year return significant wave height of Hs = 6.7 m and a peak period of Tp = 18 s (MORICHON *et al.*, 2018). Flooding events mainly result from the combination of high tide levels with extreme wave runup, through with little contribution from atmospheric surges.

2.2. Observations

In this study, the central observational data focuses on wave runup motion, continuous and in real-time. These measurements are collected by a videometry station strategically placed at +30 m within a neighboring building overlooking the beach (Figure 1). This video monitoring system is controlled by the open-source software SIRENA (MORICHON *et al.*, 2018) integrated into the KOSTASystem solution (LIRIA *et al.*, 2021). The station provides cross-shore time series of pixel intensities forming 14-minute timestack images at 1 Hz sampling frequency. The temporal evolution of waterline positions (Figure 2, blue line) is determined from the time stacks using a modified segmentation algorithm inspired by (OTSU, 1979).

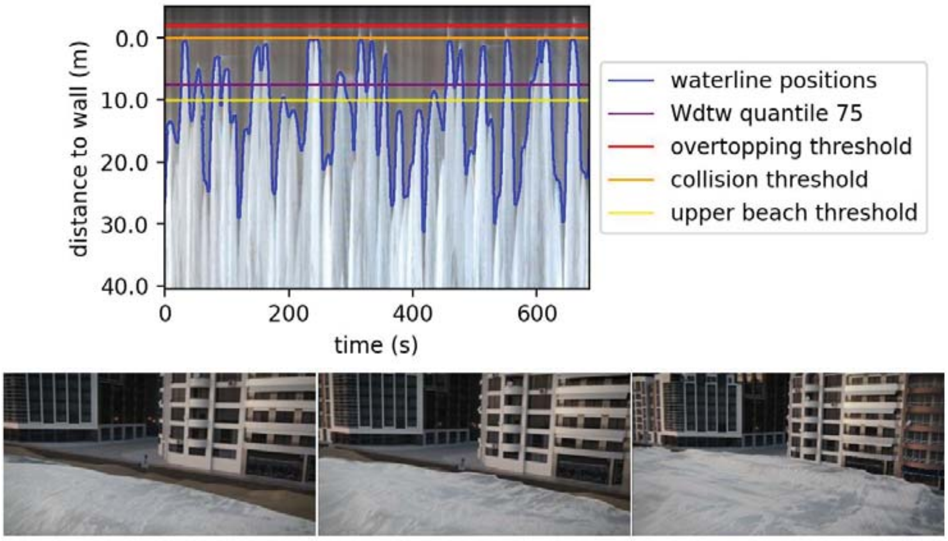

Figure 2. (Top) Processed timestack and impact indicators. (Bottom) Illustration of corresponding runup incursions: swash (left), collision (center) and overtopping (right).

The video station contributed to a multi-year database comprising around 100 historical storms from 2017 to 2023. To characterize the impact of each storm, the distance between the waterline positions and the sea wall toe *Wdtw* was computed. It was compared with representative threshold values to evaluate the occurrences of different impact regimes, namely in ascending order of intensity: swash, collision and overtopping. The quantile 75 of *Wdtw* was also computed as an additional indicator.

In addition, measurements of wave transformation processes in the surf zone carried out with an array of 5 pressure sensors are used to validate the nearshore wave model. These sensors were deployed at depths ranging from -12 m to +1 m (Figure 1) during a typical winter storm from January 31 to February 2, 2018. During this specific time window, the vertical elevation time series of the runup was also derived combining video waterline positions with topographic measurements. The reader is referred to (PINAULT *et al.*, 2022) for a detailed presentation of this dataset.

2.3. Modeling chain

An integrated modeling chain downscales regional storm predictions to the beach scale. The chain is specifically designed to calculate the total onshore water level at the individual wave scale and to forecast sea wall overtopping and flooding of the promenade. All major contributors to the onshore water level are considered: tide, atmospheric surge, and wave runup (which includes the wave setup and swash). The primary focus lies on accurately representing the significant wave runup contribution, particularly evident on the GPB.

Tide levels come from official prediction at the nearest tide gauge (SHOM). A parametric formulation accounts for the minor atmospheric surge in the study area (LENTZ & FEWINGS, 2012). The spectral wave model SWAN (BOOIJ *et al.*, 1999) simulates wave propagation from the continental shelf's outer limit to the nearshore area. The unstructured grid configuration used is described in (DELPEY *et al.*, 2021). The SWAN model provides input spectra at -20 m depth to force a phase-resolving Boussinesq-type model originally developed by (ROEBER & CHEUNG, 2012) and refined and improved in its latest version by (MIHAMI, 2023). Two configurations of the phase-resolving model are used and compared in this study: a 2D setup with a mesh size of 3 m and a 1D configuration along a cross-shore transect with a grid size of 1 m (Figure 1). Wave generation is ensured by an internal wavemaker placed at the offshore domain boundary. Wave breaking is taken into account by computing an additional governing equation for turbulent kinetic energy used as a proxy for time and space variations of an eddy viscosity diffusion term (KALISCH *et al.*, 2024). The GPU version of the model enables accelerated 2D simulations. Each model run covers a sea state of 60 min after a 20 min ramp-up with constant still water level and boundary conditions.

3. Results

3.1. Validation of the modeling chain

3.1.1. *Wave transformation and runup during a representative storm event*

The field campaign conditions on the GPB from January 31 to February 2, 2018, were re-computed using the modeling chain and compared with measurements for validation (Figure 3). The model accurately reproduces wave height evolution in the short-wave frequency band as well as the development of infragravity waves, as illustrated in Figure 3 (panels 2/3) for sensor #4 (depth = +1.15m). The modulation of wave heights with the tidal level and with the increasing energy during the storm is consistently reproduced. In 1D mode, the root mean squared error (RMSE) for Hs across the five sensors is 0.18 m, the normalized mean squared error (NRMSE) is 9%, and the Pearson correlation coefficient (R2) is 0.94. In 2D mode, the accuracy is slightly lower, RMSE is 0.21 m, NRMSE is 10% and R2 is 0.92m. When considering the runup, the 98th percentiles of video observed and modeled total water level elevations ($\eta_{2\%}$) are compared along the studied cross-shore profile in front of the Casino (Figure 3, panel 4). In 1D mode, the RMSE of the $\eta_{2\%}$ time series is 0.63 m, NRMSE is 11% and R2 is 0.87. Results are slightly better in the 2D computation, RMSE is 0.57 m, NRMSE is 10% and R2 is 0.87. These results demonstrate the capability of the modeling chain to reasonably reproduce wave transformation at and runup motion at the site under storm conditions.

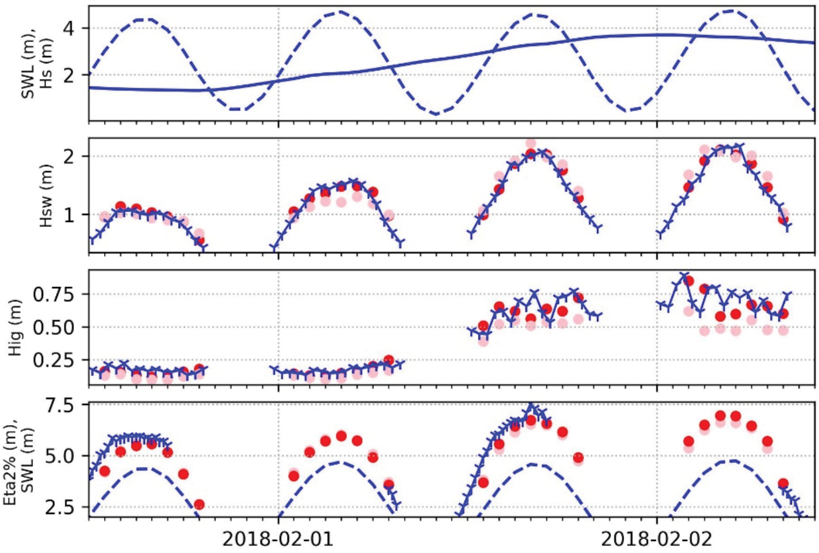

Figure 3. (Panel 1) Still water level in dashed blue, offshore H_S in solid blue. (Panel 2/3) Shortwave and infragravity significant wave heights measured (blue) and modeled by the 1D (red) and 2D (pink) phase-resolving model implementation at sensor 4. (Panel 4) Time series of $\eta_{2\%}$ and still water level (same color convention).

3.1.2. *Historical wave runup excursions in the upper beach area*

The modeling chain was executed for all storms in the historical database introduced in 0 to further evaluate its overall applicability. The model-data comparison is displayed in Figure 4 (1D mode). This result indicates a favorable agreement between observed and modeled *Wdtw*, albeit with a slight tendency to overestimate the highest *Wdtw* (*Wdtw* > 20 m). The RMSE on *Wdtw* is 6 m, with an R2 of 0.64. The number of collisions with the sea wall is also reasonably reproduced, with an RMSE of 9 occurrences per hour and an R2 of 0.57. Achieving agreement on the number of overtopping occurrences is more challenging, with an RMSE of 4 occurrences per hour and an R2 of 0.62. The model tends to overestimate the number of overtopping events, which is conservative from an application standpoint. Furthermore, the 75th quantile of the water line distance to the wall exhibits considerably less sensitivity to the phase seed compared to the 98th quantile (not shown). This difference influenced the decision to utilize the 75th quantile as an indicator in the current study.

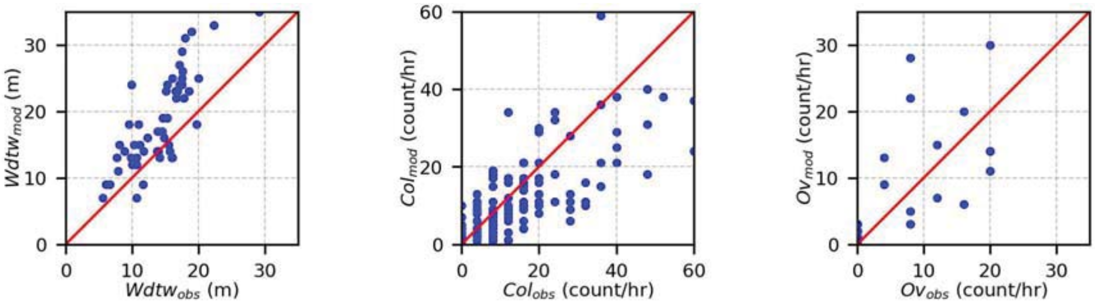

Figure 4. Observed versus modeled impact indicators. (Left) Waterline distance to the wall 75th quantile. (Center) Number of collisions. (Right) Number of overtoppings.

3.2. Early-warning and decision-support

The EWS integrates the observational and modeling components into a forecasting framework. Using GPU-based parallelization for the phase-resolving computation, the system can deliver a 5-day beach-scale prediction every 12 h without requiring excessive computational resources. During a storm event, runup levels tracked from real-time video timestacks are used to control the model prediction and to raise complementary alerts. To further support the deployment of temporary mitigation actions by Biarritz municipality, the EWS has been tailored to the city protection plan. This resulted in 6 gradual classes of storm severity each linked to specific emergency countermeasures. In the end, the obtained decision-support system provides a real-time forecast of the expected class of storm severity in the coming days that directly corresponds to the set of fitted temporary mitigation actions to be deployed by the municipality.

The effectiveness of this strategy is demonstrated through the case of the extreme storm Justine on January 31, 2021. Wave conditions off the Biarritz coastline peaked at Hs = 6.5 m and Tp = 16 s, coinciding with a high tide level of 4.6 m. The modeling chain predicted over 60 collisions and 40 overtopping occurrences per hour in front of the Casino. Additionally, the forecasted inundation maps (Figure 5) have offered valuable insights into where the most vulnerable areas are located. Inundation heights ranging from 1 m to 2 m are computed along the promenade near the Casino, with over 0.5 m observed on the southern street and parking entrance. This was proven qualitatively consistent with visual observations reported by municipal services at the storm peak. This comprehensive predicted information led to a forecasted severity level of 5 out of the 6 classes. Consequently, the Biarritz seafront was evacuated, and two rows of sandbags were strategically positioned on the promenade to shield adjacent buildings. Each bag was securely attached to the neighboring bags with a total weight of around 2 tons. The displacement of two packs of bags was observed under the effect of wave impacts during the storm. This observation underlines the severity of the event, whereas no significant damage was reported on the GPB seafront, indicating the success of the protective actions.

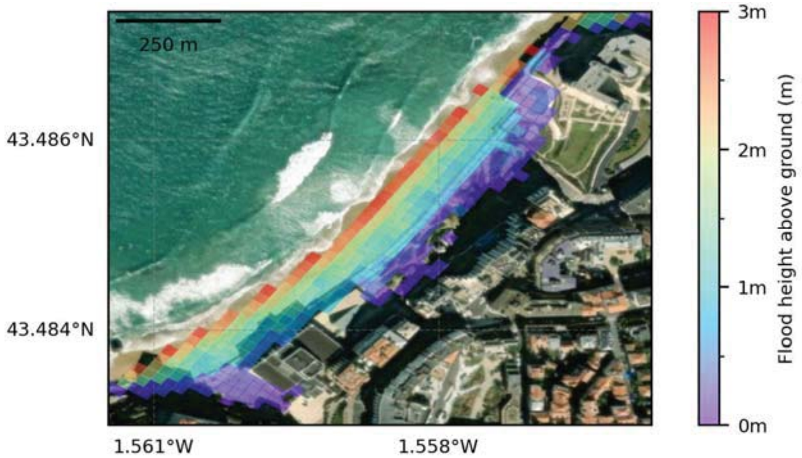

Figure 5. Forecasted inundation map for the GPB during the Justine storm.

4. Conclusions

This study introduced an innovative local-scale approach to support coastal flood wave overtopping risk management, which integrates real-time observations with high-resolution hydrodynamic modeling. The validation process confirms the modeling chain's promising ability to accurately reproduce the total onshore water level at the individual wave scale across various storm scenarios at the GPB site. The integration of the models and parameterizations forms a powerful tool for forecasting runup excursions in the upper beach area, sea wall overtopping, and promenade flooding. The collaborative design of the EWS-based decision-aid strategy with Biarritz city services ensures precise early warnings on severity classes directly linked to a set of temporary protection countermeasures. This was demonstrated during the Justine storm event. This recent case study underlines the crucial role of the proposed strategy in minimizing potential damages and ensuring public safety. The positive feedback from the practical application to the

GPB case provides an effective framework that can be generalized and replicated, offering promising applications to other coastlines critically exposed to storm wave action.

Acknowledgments

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