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Discussions

Can an early warning system help minimize the impacts of coastal storms? A case study of the 2012 Halloween storm, Northern Italy

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Early warning system in Northern Italy

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Abstract

The Emilia-Romagna Early Warning System (ER-EWS) is a state-of-the-art coastal forecasting system that comprises a series of numerical models (COSMO, ROMS, SWAN and XBeach) to obtain a daily three-day forecast of coastal storm hazard at eight key sites along the Emilia-Romagna coastline (Northern Italy). On the night of 31 October 2012, a major storm event occurred that resulted in elevated water levels (equivalent to a 1-in-20 to 1-in-50-year event) and widespread erosion and flooding. Since this storm happened just one month prior to the roll-out of the ER-EWS, the forecast performance related to this event is unknown. The aim of this study was to therefore reanalyse the ER-EWS as if it had been operating a day before the event and determine to what extent the forecasts may have helped reduce storm impacts. Three different reanalysis modes were undertaken: (1) a default forecast (DF) mode based on three-day wave and water-level forecasts and default XBeach parameters, (2) a "perfect" offshore (PO) forecast mode using measured offshore values and default XBeach parameters; and (3) a calibrated XBeach (CX) mode using measured offshore values and an optimized parameter set obtained through an extensive calibration process. The results indicate that while a "code red" alert would have been issued for the DF mode, an underprediction of the extreme water levels of this event limited high-hazard forecasts to only two of the eight ER-EWS sites. Forecasts based on measured offshore conditions (the PO mode) more-accurately indicate high hazard conditions for all eight sites. Further considerable improvements are observed using an optimized XBeach parameter set (the CX mode) compared to default parameters. A series of what-if scenarios at one of the sites show that artificial dunes, which are a common management strategy along this coastline, could have hypothetically been constructed as an emergency procedure to potentially reduce storm impacts.

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1 Introduction

The last decade has seen some particularly large coastal storms that have severely tested and, tragically, demonstrated certain limitations of established disaster risk reduction (DRR) measures. This list includes Hurricane Katrina that struck the coastline of Louisiana in 2005 (Knabb et al., 2005), Cyclone Sidr in the Bay of Bengal in 2007 (Paul, 2009) the 2010 Xynthia storm on the west coast of France (Kolen et al., 2013), Hurricane Sandy on the east coast of the USA in 2012 (Galarneau Jr. et al., 2013), Typhoon Haiyan in the Phillipines in 2013 (Lagmay et al., 2015) and the 2013/14 series of winter storms in the UK (Slingo et al., 2014). Whether or not these events have increased in both intensity and frequency in the long term is the subject of considerable debate (Coumou and Rahmstorf, 2012; Peterson et al., 2013). An increase in exposure to these storm hazards due to factors such as the increase in people and economic assets in low-lying areas (Lavell et al., 2012) nevertheless places increasing pressure to review and update DRR strategies regardless of any storm trends.

A key aspect of DRR measures is that of community preparedness, of which early warning systems (EWSs) play a vital role (Lavell et al., 2012). Early warning systems involve the provision of timely (i.e., a sufficient preparation window prior to the approaching hazard) and effective (i.e., accurate and clear) information so that the exposed individuals can undertake the necessary actions in order to avoid or minimize their risk (Basher, 2006). With specific regards to coastal storm hazards, the development of EWSs has until recently focused on hydrodynamic forecasts for vulnerable low-lying areas. Some examples of these systems around the world include the *acqua alta* surge forecast system for Venice lagoon (Ferrarin et al., 2013; Mariani et al., 2015), the UK joint Met Office/EA Flood Forecasting Centre (Stephens and Cloke, 2014), the US National Hurricane Center forecast system (Morrow et al., 2015) and the Bangladesh storm surge EWS (Dube et al., 2009). When performing successfully, the early warnings provided by these systems have been credited with

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having greatly reduced the impacts and loss of life of various extreme events (e.g. Paul, 2009; Stephens and Cloke, 2014; Spencer et al., 2014).

For areas where sandy barriers provide a degree of protection from coastal storms, the inclusion of morphological processes in coastal hazard forecasts is critical (Ciavola et al., 2014). Waves and currents interact with beach and dune sediments during storms to dissipate wave energy and act as a natural defence against storm surge. Dune or barrier breaching as a result of erosion and overwash on the other hand can potentially have devastating effects on the coastal hinterland by causing a sudden ingression of marine water and widespread flooding. Recent advancements in coupled hydrodynamic-morphodynamic models such as XBeach (Roelvink et al., 2009) have enabled these processes to be simulated with enhanced accuracy and numerical efficiency. XBeach has been shown to successfully model a diverse range of extreme scenarios, such as hurricane impacts on barrier islands (McCall et al., 2010), coastal inundation on beaches protected by rubble mound breakwaters (Harley and Ciavola, 2013), dune erosion during Australian east coast lows (Splinter and Palmsten, 2012) and maximum wave run-up (Stockdon et al., 2014).

Prototype EWSs for coastal storm hazards that include both hydrodynamic and morphodynamic processes have begun to recently emerge in both the USA and Europe. The Coastal Storm Modeling System (CoSMoS) has been developed for the US west coast to provide detailed deterministic predictions of storm impacts for both coastal vulnerability assessments and real-time forecasts (Barnard et al., 2014). It comprises a numerical model chain from large-scale atmospheric and wave forecasts down to detailed (i.e., meter-scale) predictions of coastal hazards at a series of closely-spaced cross-shore transects along the coastline. In Europe, the MICORE project (Morphological Impacts and COastal Risks induced by Extreme storm events, Ciavola et al., 2011b, a) established a series of prototype EWSs at nine diverse sites using a similar methodology to that of CoSMos but with a strong end-user focus through the application of Storm Impact Indicators (SIIs, Ciavola et al., 2011b). These SIIs are based on the "Frame of Reference" approach of Van Koningsveld and Mulder (2004)

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and are used to translate the comprehensive and sometimes complex model output into a clear format useful for decision making in emergency scenarios.

This study presents the EWS for coastal storm hazard initiated as part of the MICORE project for the coastline of Emilia-Romagna, Northern Italy. The Emilia-Romagna coastline is situated on the Adriatic Sea and is particularly vulnerable to coastal storms due to its low-lying nature (exacerbated by decades of anthropogenic and natural land subsidence, Teatini et al., 2005), the large amount of infrastructure concentrated close to the coastline as well as the frequency of winter storm events with water levels exceeding those of the dune crest and building foundations. A common practice undertaken by beachfront property owners in Emilia-Romagna in order to manage this storm risk is the artificial modification of the beach profile by means of beach scraping (Armaroli et al., 2012; Harley and Ciavola, 2013). Prior to the upcoming winter, an artificial dune of approximately 3 m in height above mean sea level is scraped from available sub-aerial beach sand and used as a soft revetment from storm waves and elevated water levels. The relatively ad hoc nature of this management technique however means that these artificial dunes often fail for particularly large events, causing flooding of properties in their lee. When storm events subside in the spring months (i.e., April–May), these dunes are subsequently removed and the profile reshaped to its pre-modified form. Artificial dunes are also used as a coastal management technique across many parts of the USA (e.g. McNinch and Wells, 1992; Gallien et al., 2015) Europe (e.g. Matias et al., 2005) and Australia (e.g. Carley et al., 2010).

The Emilia-Romagna EWS – hereafter referred to as the ER-EWS – has been operational (in experimental mode) since December 2012 as a partnership between the University of Ferrara, the Hydro-Meteo-Climate Service of Emilia-Romagna (ARPA-SIMC) and the Geological-Seismic-Soil Service of Emilia-Romagna (SGSS). One of the principal goals of the ER-EWS is the ability to predict with sufficient warning and accuracy both the amount of dune erosion as well as the location, timing and extent of marine flooding along this coastline. To this end, a chain of atmospheric, hydrodynamic and morphodynamic models are executed daily to obtain a three-day prediction of

coastal hazard at various strategic locations alongshore. The state-of-the-art nature of this system however means that a detailed understanding of the system performance is required.

On the night of 31 October 2012, a large storm occurred in the Adriatic Sea that resulted in elevated water levels along the entire Emilia-Romagna coastline and characteristic of a 1-in-20 to 1-in-50-year event (Masina and Ciavola, 2011). Referred to in the media as the "Halloween storm", the resulting widespread coastal flooding and erosion called into question whether more effort was needed to enhance the regional preparedness to such events. Since the Halloween storm occurred just one month prior to the roll-out of the ER-EWS, the extent to which such a warning system could have helped reduce these impacts is unknown. This study therefore evaluates this event by reanalyzing the ER-EWS predictions as if it were operational one day prior to the storm. The results of this analysis have the following aims: (1) to quantify the accuracy of the EWS predictions with respect to measured data, (2) to assess potential weaknesses in the early warning system model chain, and (3) to undertake "what if" scenarios with regards to the presence/absence of artificial dunes of various dimensions.

2 Background

2.1 Study area

The Emilia-Romagna coastline is situated on the northern Adriatic Sea and comprises 130 km (from the Po Delta at its northern boundary to the township of Cattolica at its southern boundary) of predominantly sandy beaches (Fig. 1). It is a highly-modified coastline, with over half (57 %) of the region protected by coastal structures such as rubble-mound breakwaters, groynes and seawalls (Perini et al., 2008). These modifications have been built primarily over the last 60 years in conjunction with the large growth in tourism on this coastline, which now amounts to approximately five million tourists visiting each year (Union Camere, 2013). Tourist areas are concentrated

in the southern section of the region, particularly in the major townships of Rimini, Riccione and Cesenatico. Stretches of natural areas meanwhile are more common on the central and northern parts of the coastline and typically have relatively small foredunes of up to 4 m in height, a flat beach slope ($\tan\beta \approx 0.03$) and a dissipative beach state (Armaroli and Ciavola, 2011).

Environmental conditions for the region are characterized by low wave energy (mean $H_{sig} \approx 0.4$ m, $T_{peak} \approx 4$ s) with a semidiurnal and micro tidal regime (neap tidal range = ±0.15 m, spring tidal range = ±0.4 m). Storm waves meanwhile of up to 3.3 m (1 in 1-year return period, Armaroli et al., 2009) and storm surge anomalies of up to 0.6 m (1 in 2-year return period, Masina and Ciavola, 2011) can occur, particularly in the winter months. These storm waves are mainly from the east to northeast sectors associated with *Bora* weather conditions. Surge events meanwhile predominantly occur during south-easterly (*Scirocco*) winds, which coincide with the main SE–NE axis of the Adriatic Sea. *Bora* storm waves are generally large and steep, whereas *Scirocco* waves are smaller but with a longer wave period. This is because the latter are generated over a longer fetch but with winds of lower intensity. SE waves are also sheltered somewhat by Conero Headland south of Emilia-Romagna.

2.2 The Emilia-Romagna early warning system

Within the existing civil protection protocol for the Emilia-Romagna coastline, three-day wave and water-level forecasts are undertaken daily by ARPA-SIMC through its meteo-marine operational forecasting system (Russo et al., 2013). Wave forecasts are performed using the shallow-water wave model SWAN (Booij et al., 1999), forced with 10 m wind output from the atmospheric model COSMO-I7 (7 km resolution, www.cosmo-model.org). A nested computation grid is used for SWAN model runs, from a 25 km grid resolution of the Mediterranean Sea to an 8 km intermediate grid of the Italian region and finally a high-resolution 800 m grid of the Emilia-Romagna coastline (Valentini et al., 2007). Three-day water-level forecasts are undertaken using the ocean model ROMS (Haidvogel et al., 2008) for the entire Adriatic Sea at a regular

grid resolution of 2 km. The ROMS model is forced by atmospheric output (10 m wind, sea level atmospheric pressure etc.) from COSMO-I7, with the main semidiurnal (M2, S2, N2) and diurnal (K1, O1) tidal components and measured or monthly-average river discharge values used as forcing conditions. For a complete description of the meteo-marine forecasting system for Emilia-Romagna, see Russo et al. (2013).

The ER-EWS extends this existing offshore forecast system into the coastal zone through the addition of XBeach (Fig. 2). XBeach is a two-dimensional depth-averaged (2DH) model that solves coupled cross-shore and alongshore equations for wave propagation, flow, sediment transport and bed-level changes (Roelvink et al., 2009). It has been designed primarily as a dune and barrier island erosion model based on the four stages of dune impacts described by Sallenger (2000). The main innovation of XBeach compared to other similar models is that surf and swash-zone processes are solved on the time-scale of wave groups, which drive infragravity wave motions that become increasingly dominant as the surf zone becomes saturated (Ruessink et al., 1998). Infragravity waves are therefore the most likely cause of wave bore collisions with the dune face during storm events (Roelvink et al., 2009). An avalanching algorithm is used to simulate the effects of slope collapse during these bore collisions (Van Thiel de Vries, 2009). For a complete description of the XBeach model setup, see Roelvink et al. (2009).

Two different SIIs (Fig. 3) are used within the ER-EWS to translate XBeach predictions into indicators of storm hazard, as selected by the Regional Geological Survey and ARPA to monitor storm impacts and compile them into an impact-oriented event database (Perini et al., 2011). The first SII is applicable to stretches of coastline with natural dunes and is called the Safe Corridor Width (SCW). The SCW is a measure of the amount of dry beach available between the dune foot and waterline for safe passage by beach users and is given by:

$$\text{SCW}(t) = X_{\text{df}} - X_{\text{wl}}(t), \tag{1}$$

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where X_{df} is the surveyed cross-shore position of the dune foot and X_{wl} is the model-derived position of the waterline that varies through time due to tidal variability, storm surge, wave set-up/run-up and erosion of the beach face. If the SCW becomes too narrow then people could be putting their lives at risk by having no means of escaping the hazardous marine conditions. A threshold SCW of 10 m has been selected by end users to separate low hazard (i.e., "code green") conditions from medium hazard (i.e., "code orange") conditions. A threshold SCW of 5 m meanwhile has been selected to separate medium hazard conditions from high hazard (i.e., "code red") conditions.

The second SII used within the ER-EWS is applicable to locations with beachfront infrastructure and is referred to as the Building-Waterline Distance (BWD). Similar to the SCW, the BWD is a measure of the amount of dry beach available between the seaward edge of a building and the model-derived waterline. It is given by:

$$BWD(t) = X_b - X_{wl}(t), \qquad (2)$$

where X_b is the surveyed cross-shore position of the seaward edge of the building. A threshold BWD of 10 m has been selected by end users to separate low hazard conditions from medium hazard conditions. A threshold BWD of 0 m (i.e., inundation of the building is predicted) has meanwhile been selected to separate medium hazard conditions from high hazard conditions.

The complete model chain is executed daily at a total of 22 cross-shore profile lines along the Emilia-Romagna coastline. These profile lines correspond to eight different coastal sites, including the tourist areas of Rimini, Cesenatico and Riccione. Table 1 summarizes the various beach statistics of each site. Dry beach widths, defined as the distance from the dune foot or building edge to mean sea level, vary from site to site from a minimum of 21 m at the site of Lido di Classe to a maximum of 160 m at Lido di Spina. Grain size information for each site was obtained from SGSS and range between 120 and 230 μm (D_{50}).

Given the impracticalities and costs of continuously updating profile lines, daily simulations are undertaken by using the same initial profile line. For most ER-EWS

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sites, the topographic data used to obtain these initial profiles are derived from a Lidar survey conducted along the entire coastline in March 2010. Having been undertaken towards the end of the winter season, these profile shapes are characteristic of a more-conservative eroded winter beach profile. A consequence of using this one-off survey of the entire region is that some profiles contain artificial dunes and others not (see Table 1). This introduces local variability to the hazard forecasts depending on how the beach profile was modified at the time.

The exception to this pragmatic approach to updating initial profile lines is the site of Lido di Classe, which is used as a validation site for the ER-EWS and is subject to regular (approximately every two months during winter and after major storm events) topographic beach surveys using RTK-GPS technology (Fig. 4). Lido di Classe is a double-barred sandy beach of approximately 30 m in width and has natural vegetated foredunes backed by a low-lying pine forest (Armaroli et al., 2013). Eleven closely-spaced (alongshore spacing = 250 m) profile lines over a 2.5 km stretch are used for validation, with dune crests ranging from 2.1 m at the southernmost profile (profile name *classe11*) to 3.9 m at the northernmost profile (profile name *classe01*).

Daily ER-EWS hazard predictions for the regional authorities are displayed on a WebGIS platform. The home page (Fig. 5a) presents a general overview of the current state of the region in terms of coastal hazard for the next three days, with pin colors (i.e. green, orange or red) corresponding to the worst predicted hazard level for each site. Zooming into individual profile lines (Fig. 5b) subsequently indicates the maximum (i.e. most landward) position of the predicted waterline over the following three days as well as the corresponding SII time series (Fig. 5c). An automated email service is also active and sends emails to the relevant authorities when any predictions exceed the designated threshold levels.

2.3 The 2012 Halloween storm

Beginning in the afternoon of 31 October 2012, a cyclonic system centred over the Ligurian Sea resulted in strong SE (i.e., *scirocco*) winds blowing over the length of

the Adriatic (Mariani et al., 2015). At Ravenna, wind speeds began to develop from 15:00 GMT and peaked at a value of $15.5\,\mathrm{m\,s^{-1}}$ (approx. $60\,\mathrm{km\,h^{-1}}$) at 21:50 GMT. The intensity and fetch length of this wind created a strong surge event that resulted in water levels reaching a maximum at the Ravenna tide gauge of 1.16 m above mean sea level at 23:30 GMT, the equal highest level recorded in the gauge's 15-year history. In Venice meanwhile, water levels peaked at 1.43 m (according to the Venice reference level), which is the equal 14th highest level recorded since 1923 and was sufficient to flood approximately 60 % of the city.

Wave conditions during the storm were measured by the Cesenatico wave buoy, located off the coastline of Cesenatico in 10 m water depth (Fig. 1). According to these measurements, significant wave heights (H_{sig}) peaked at a value of 2.43 m at 03:00 GMT on 1 November, which when considered in isolation to the extreme water levels represents only a relatively minor storm event for this coastline (Armaroli and Ciavola, 2011). Wave periods during the height of the storm were around 10 s and the wave direction was from the east. Both wave and water levels decreased by the following afternoon, such that the entire event duration was less than 24 h. Damage due to the event however was extensive across the whole northern Adriatic Sea. In Emilia-Romagna, inundation and erosion was observed along the entire 130 km coastline, including the destruction of several beachfront restaurants, flooding of villages, major road blockages and sunken boats moored at marinas. A lower estimate of the damage bill for the Emilia-Romagna coastline was placed at EUR 4.6 million (SGSS Emilia-Romagna, 2013), which does not include the considerable flood damage to private infrastructure.

At the Lido di Classe validation site, the low dune crest elevations of the two southernmost profiles (*classe10* and *classe11*) meant that overwash occurred at these locations (Fig. 4b and c). The other nine profiles, where the dune crests are higher, underwent dune face erosion but no overwash. Pre- and post-storm RTK-GPS surveys were performed (both topographic profile-line and maximum waterline measurements) and used to calculate the degree of sub-aerial beach erosion (ΔV, defined by the

volume above mean sea level) and the minimum SCW according to Eq. (1). A negative minimum SCW was observed at all eleven profile lines, meaning that the maximum waterline exceeded the initial dune foot position along the entire site (Fig. 4d). This was particularly the case for the two southernmost profiles, where overwash resulted in strongly negative values of the SCW (measured minimum SCW at *classe11* = −26 m).

3   Methods

3.1   EWS reanalyses

Three different EWS reanalysis modes were undertaken in order to obtain a detailed understanding of the EWS performance for the Halloween storm. These reanalyses concentrated first on the eleven cross-shore profile lines at the Lido di Classe validation site, followed by an overall reanalysis of all eight ER-EWS sites. The three reanalysis modes are described below.

3.1.1   Default Forecast (DF) mode

The Default Forecast mode (hereafter referred to as the DF mode) consisted of running the ER-EWS model forecast chain as if it had been operating at 00:00 GMT on 31 October 2012 i.e., approximately 15 h prior to the onset of the storm. In order to undertake this reanalysis, three-day wave and water-level predictions for 31 October were extracted from the SWAN and ROMS model prediction archive at each of the eight ER-EWS sites. These output time-series were then used as boundary conditions to run XBeach (revision 4242) for the 22 cross-shore profile lines. No XBeach calibration was undertaken for the DF mode, meaning that all XBeach model parameters were set to default values.

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3.1.2 "Perfect" Offshore forecast (PO) mode

In addition to the DF mode, coastal hazard forecasts based on "perfect" (i.e., identical to measured conditions, not considering measurement errors) offshore forecasts were also calculated using the wave and water-level measurements between 31 October and 2 November 2012. This Perfect Offshore forecast mode (hereafter referred to as the PO mode) was undertaken to remove the influence of wave and water-level prediction uncertainties and focus solely on the XBeach model prediction accuracy. Wave conditions were assumed to be constant along the Emilia-Romagna coastline and extracted from the Cesenatico wave buoy. Water-level measurements were meanwhile taken from the Ravenna tide gauge (see Fig. 1 for locations). Similar to the DF mode, default XBeach parameters were used for this mode.

3.1.3 Calibrated XBeach (CX) mode

The final reanalysis mode consisted of adjusting the PO mode to contain calibrated (as opposed to default) XBeach model parameters. Hereafter referred to as the CX mode, this reanalysis represents what should be the most precise forecasts of region-wide coastal hazard for this storm event by using both actual offshore wave and water-level measurements as well as a rigorous calibration of the XBeach model to reflect the site and event-specific conditions.

Calibration of the XBeach model parameters was undertaken using the beach profile and maximum waterline measurements at the eleven Lido di Classe profile lines. The calibration concentrated on a number of XBeach parameters deemed critical to wave run-up and beach/dune erosion processes for this particular type of event and coastal setting:

- *maximum shields value for overwash processes (smax)*. It has been observed that XBeach tends to overestimate erosion rates during overwash conditions when the sediment concentration is high and sheet flow conditions occur (McCall et al., 2010). This parameter therefore limits sediment transport during sheet flow to

a linear function of flow discharge. Similar to McCall et al. (2010), a value of 0.8 was tested against the default setting (default = no limiter);

– *breaker index in dissipation model (gamma)*. Energy dissipation due to wave breaking is calculated in XBeach using the formulation of Roelvink (1993). This equation has three calibration parameters: a power term (*n*, default = 10), a parameter to adjust the dissipation rate (alpha, default = 1.0) and a parameter to adjust the fraction of wave breaking depending on water depth (gamma, default = 0.55). Default settings of *n*, alpha and gamma are based on a limited number of tests undertaken predominantly in the wave flume. A variation of these settings (gamma = 0.42) was tested for the calibration process here, which has been found (Stockdon et al., 2014) to result in improved estimation of maximum run-up at Duck, USA, a sandy beach with similar environmental characteristics (i.e., barred profile, microtidal) to those in Emilia-Romagna;

– *maximum allowed wave height over water depth (gammax)*. This limiter restricts wave heights in very shallow water. A value of 1.5 (meaning that maximum wave heights are restricted to 1.5 times the water depth) was tested against the default value (gammax = 2.0);

– *threshold depth between wet/dry points (eps)*. This parameter determines the critical depth that defines wet grid points from dry grid points and is hence important for shallow water processes as well as determining X_{wl} in Eqs. (1) and (2). Similar to Splinter and Palmsten (2012), values of 0.01 and 0.1 were tested against the default value (eps = 0.005);

– *critical avalanching slope under water (wetslp)*. This parameter determines the maximum bed slope for wet grid points prior to slumping. A maximum slope of 0.5 was tested against the default value (wetslp = 0.3);

– *wave asymmetry parameter (facua)*. This parameter, which can vary between 0 and 1, determines the degree to which short wave asymmetry and skewness

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control the direction of sediment transport. Similar to Splinter and Palmsten (2012), a value of 0.15 was tested against the default value (facua = 0.1).

An iterative procedure involving 32 different model runs for each profile (total model runs = 352) was undertaken in order to obtain the optimum parameter settings. Model performance was assessed by comparing model output to both the measured minimum SCW/maximum waterline (see Fig. 4d) and the measured sub-aerial beach volume change (ΔV). The parameter set that resulted in the most-accurate estimations of these two performance criteria was subsequently chosen as the optimum parameter set to be used for the CX mode.

3.2 What-if scenarios based on alternative artificial dune designs

The second component of the study was to undertake what-if scenarios in order to assess the degree to which artificial dunes may have helped reduce the widespread flooding that occurred. Given the relatively short time-frame (i.e., < 6 h) required to construct such temporary coastal defence measures, Harley and Ciavola (2013) suggested a new coastal management technique whereby these dunes are used in conjunction with real-time forecasts as an emergency reinforcement measure prior to storm arrival. A numerical tool known as DuneMaker (Harley, 2014) was subsequently developed to rapidly test the impact of different artificial dune configurations for a given forecast condition. This tool, which has been designed based on real cases in Emilia-Romagna, simulates the action of a bulldozer in scraping sub-aerial beach sand in order to form a dune of a certain height (Z_{crest}), width (W_{crest}), cross-shore position (X_{crest}) and slope (m).

The profile line at Rimini towards the south of the Emilia-Romagna coastline was chosen to undertake such an analysis. With a maximum profile elevation of just 1.5 m and a large amount of tourist infrastructure concentrated on the beach itself, this site was particular hit by the Halloween storm and resulted in damage of approximately EUR 1.1 million (SGSS Emilia-Romagna, 2013). Eight different dune designs were

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tested and compared to the actual conditions whereby no artificial dune was present. These dune designs were divided into two sets of four dune designs: one set where a buffer of 15 m exists between the artificial dune and the seaward edge of the building (Fig. 6a) and another set closer to the shoreline with a buffer of 55 m (Fig. 6b). In each set, the dune crest height varies in 0.5 m increments between 1.5 and 3.0 m and the crest width altered accordingly in order to maintain a comparable dune volume. Seaward and landward dune slopes were fixed in all cases at 0.25 and 0.75 respectively, which are typical values for the Emilia-Romagna coastline (Harley and Ciavola, 2013).

Only the CX forecast mode was used to undertake these what-if scenarios, since this mode represents what should be the most precise of the three forecast modes. The ability of each dune to retain the elevated water levels and wave action was assessed using two parameters: (1) the minimum BWD obtained over the forecast period; and (2) the percentage of artificial dune volume remaining following the storm event. Whereas the minimum BWD determines whether or not building inundation occurs, the percentage of dune volume remaining gauges the degree to which each dune is able to resist the storm.

4 Results

4.1 SWAN and ROMS forecasts

An important first assessment of the overall ER-EWS performance is the accuracy of the offshore wave and water-level forecasts derived from the ROMS and SWAN model respectively. Results of these three-day forecasts for the 31 October 2012 forecast date are plotted against co-located wave and water level measurements in Fig. 7. The results indicate that the SWAN model predicted the observed peak H_{sig} of 2.43 m to a high degree of accuracy (forecast peak H_{sig} = 2.35 m), but underestimated the duration of the storm. In terms of period and wave direction (not shown), the SWAN

model also reasonably forecast the peak period (measured peak period = 10.0 s, forecast peak period = 10.2 s) as well as the direction of the storm (measured direction at peak of storm = 90°, forecast direction = 103°).

Comparisons between water-level forecasts and measured values show that the forecasts quite significantly underestimated the extreme water levels over the entire duration of the event. Whereas water levels were observed to peak at 1.16 m in Ravenna, forecasts derived from the ROMS model only predicted a peak of 0.87 m. Additionally whereas the measurements indicate that these extreme levels were maintained for approximately 12 h, the forecasts indicate a drop in water levels following this peak. Such a significant underestimation of the water level over the duration of the event has implications for the three different forecast reanalyses presented below.

4.2   Forecast reanalyses: Lido di Classe validation site

Results of the forecast reanalyses in terms of both the minimum SCW and ΔV predicted at the eleven Lido di Classe profiles are summarized in Table 2, with each profile classified according to the Sallenger (2000) dune impact regime (CO = collision regime, OW = overwash regime).

Considering the DF forecast mode, the results indicate that while predictions for this mode exceed the high hazard threshold for all eleven profiles (average forecast minimum SCW = −3 m), an overall underprediction of the maximum waterline reached by the Halloween storm is found. This underprediction is greatest at the southern end of the site where the dune crest is lowest and overwash occurred. In terms of the sub-aerial beach volume change, this same mode resulted in a slight overestimation in the degree of sub-aerial beach erosion.

The PO forecast mode takes into account the measured extreme water levels and consequently results in significantly different forecasts in comparison to the DF mode. Whereas the DF mode underpredicts the maximum waterline due to the Halloween storm, the PO mode significantly overpredicts this position. At all eleven profile lines, the waterline for this mode is forecast to overtop the dune crest and continue down

into the low-lying pine forest backing the dunes. Values of the minimum SCW are subsequently in the range of $-16\,\mathrm{m}$ (*classe08*) to $-86\,\mathrm{m}$ (*classe10*). A similar overprediction is found when considering predictions of ΔV for this mode, with the forecast sub-aerial beach erosion almost an order of magnitude greater than measured values.

Switching from the default XBeach parameter set to an optimized set results in further differences to the coastal hazard forecasts. An optimized parameter set consisting of smax = 0.8, eps = 0.1, gamma = 0.42 and facua = 0.15 was obtained through the calibration process of 352 different model runs detailed in Sect. 3.1.3. The use of this optimized parameter set results in major improvements to the maximum waterline predictions in comparison to the PO mode. The forecast minimum SCW for all but the two southernmost profiles (*classe10* and *classe11*) is comparable to observed values, with an average difference between forecasts and measurements at these nine profile lines of just 1 m. A similar outcome is observed for the sub-aerial beach erosion forecasts, where the average ΔV for nine of the eleven profiles (again excluding the two southernmost profiles) is $12\,\mathrm{m^3\,m^{-1}}$ and represents only a slight overestimation of measured values. For the two southernmost profiles, the calibration process makes little difference to the large overestimation of both the maximum waterline and ΔV that was observed in the PO forecast mode.

Figure 8 illustrates the differences between the coastal hazard predictions for the different reanalysis modes at the second northernmost profile *classe02*. The figure indicates that the DF mode results in a reasonable prediction of beach profile change, but an underestimation of the minimum SCW. On the other hand the PO mode indicates a major overestimation of the beach profile change as well as the maximum waterline. Finally the CX mode displays only a slight overestimation of the beach profile change and a near-perfect (i.e., within 1 m cross-shore) prediction of the minimum SCW.

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4.3 Forecast reanalyses: regional level

At the regional level, the three reanalysis modes indicate disparate forecasts of coastal hazard for the Halloween storm (Fig. 9). For the DF mode, the reanalysis shows that only two of the eight sites (Marina Romea and Lido di Classe) would have issued high hazard forecasts had the ER-EWS been operating on 31 October 2012. Both of these sites correspond to natural areas where the SCW is predicted and the dry beach width is particularly narrow. For all other sites (including the site of Rimini) the DF mode would have mistakenly forecast low hazard conditions, implying that no major threat to buildings or dune systems was imminent at these sites.

In contrast to the DF mode, all eight ER-EWS sites in Fig. 9 indicate "code red" conditions meaning that high hazard conditions would have been forecast. Since some of these sites include artificial dunes in the topographic data (see Table 1), this suggests that these dunes would have failed for this particular storm and the waterline would have subsequently reached the buildings (i.e., BWD = 0 m).

Finally, the CX mode shows that six of the eight sites would have issued a high hazard forecast. The two sites where low hazard conditions would have been forecast are those of Riccione and Cesenatico. These sites correspond to profiles where particularly high artificial dunes are present in the topographic data and closer inspection (not shown) of the forecast simulations indicate that these dunes were capable of retaining the elevated water levels and waves of the Halloween storm. This concept is explored in greater detail in the results of the what-if scenarios for artificial dunes below.

4.4 What-if scenarios for artificial dunes at Rimini

The reanalysis of the ER-EWS above indicate that the CX mode would have forecast high hazard conditions for the low-lying and dune-free Rimini site. Had this hypothetical forecast been available a day before the Halloween storm, the what-if scenarios based on the eight different artificial dune configurations would subsequently have provided

a valuable means of testing and optimizing potential emergency dune constructions prior to the storm arrival. The results of these scenarios (Table 3) indicate that all dunes barring those with the lowest crest elevations (Dunes 1 and 5, $Z_{crest} = 1.5$ m) would have resulted in significant reductions to the hazard forecasts, from a high hazard forecast for building inundation down to a low hazard forecast. Furthermore these artificial dunes appear relatively resistant to erosion for the Halloween storm, since the percentage of dune volume remaining in all cases except for Dunes 1 and 5 is at least 87 %. In the cases of artificial dunes built further away from the shoreline (i.e., Dunes 2–4), these dunes are seen to actually increase in volume, as a fraction of the sediment eroded close to the shoreline accumulates at the base of the dune.

5 Discussion

This case study for the 2012 Halloween storm in Northern Italy highlights both the current challenges but also the great potential of early warning systems as a tool for coastal management in the future. The challenges lie in the fact that uncertainties in the deterministic forecasts can be introduced from a large number of sources and subsequently propagate along the forecast model chain. With regards to the Halloween storm, three main sources of uncertainty appear to limit the overall forecast accuracy:

5.1 Uncertainties due to offshore water-level forecasts

Water-level forecasts derived from the ROMS model were found to underpredict the extreme water levels over the duration of the Halloween storm. For a low-lying coastline like Emilia-Romagna, this underprediction made the difference between low hazard "code green" forecasts along most of the coastline and high hazard "code red" forecasts for all eight ER-EWS sites. While discerning the causes of the water-level underpredictions for this storm are beyond the scope of this study, it is worth noting that a similar result was observed for the same event by the *acqua alta* surge forecast system in Venice, just to the north of the study region (Mariani et al., 2015). Following

an extensive review of the possible forecasting errors related to this event, Mariani et al. (2015) attributed the underprediction of the surge in Venice predominantly to the forecast complexity of this particular storm, which consisted of complex localized wind fields that amplified the degree of surge at certain locations.

5.2 Uncertainties due to XBeach parameterization

Comparisons between forecasts based on default XBeach parameters and an optimized parameter set obtained through the testing of six different parameters also resulted in significant differences to the overall coastal hazard forecasts. In general, the default XBeach settings were found to significantly overpredict the maximum waterline and degree of sub-aerial beach erosion for this event. Improvements to the model predictions were observed as parameters were changed one-by-one from their default settings. Specifically, the shields limiter smax resulted in the most notable model improvements for this event, followed in order of influence by the parameters gamma, eps and facua. Note that no significant prediction changes were observed for the parameters gammax and wetslp based on the values tested. The optimized parameter set using these four parameters resulted in satisfactory results from an end-user perspective, with a mean error in the maximum waterline predictions of only 1 m for nine out of the eleven profile lines tested. A significant overprediction of the maximum waterline and sub-aerial beach volume change for the two southernmost profile lines where overwash occurred was however still observed, which suggests that further improvements need to be made to the XBeach model under overwash conditions.

5.3 Uncertainties due to coastal topography

With the exception of the Lido di Classe validation site, topographic data used to perform the forecast reanalyses were derived from a region-wide Lidar flight undertaken in March 2010. While the Emilia-Romagna coastline can be considered relatively stable in comparison to more exposed coastlines, the use of this two-year-

old topographic data introduces a degree of uncertainty into the forecasts. This is particularly the case when considering the artificial modification of the beach profile, which is undertaken on an ad hoc basis along the coastline and can vary considerably from year to year.

Addressing the above uncertainties can be achieved in part through a combination of numerical model improvements, enhanced coastal monitoring and comparable studies of other major storm events. As a means of reducing uncertainties in the water-level forecasts for instance, steps are currently being made to upgrade and improve the offshore forecasting system by increasing the model resolution, coupling the SWAN and ROMS models as well as including additional tidal components and river flow inputs (Russo et al., 2013). Coastal monitoring has also been increased through the use of real-time video imaging in order to provide a more precise snapshot of the current state of the coastline, including the size and location of artificial dunes (Armaroli and Ciavola, 2011; Harley and Ciavola, 2013).

While these measures are likely to improve the confidence of coastal hazard forecasts, uncertainties will always remain. Baart et al. (2011) discusses various methods of estimating confidence intervals of morphological forecasts through the use of ensemble forecasting (i.e., performing multiple runs by slightly varying the input conditions) as well as long-term observations of morphological forecast error. As this study has demonstrated, ensemble forecasting should ideally require multiple permutations of not only the offshore forecasts, but also of different XBeach parameter sets and variations in coastal topography (e.g. natural vs. artificially-modified and eroded vs. accreted beach profiles). While this would lead to a significant increase in forecast computation time, a greater understanding of the forecast uncertainty would be achieved in order to better inform decision makers. Long-term observations of morphological forecast error on the other hand requires several years of monitoring data that is currently unavailable.

Despite these challenges, the benefits of an operational forecasting system for the Emilia-Romagna coastline are clearly apparent. Considering the site of Rimini, the

series of what-if scenarios suggest that an artificial dune with a crest elevation of at least 2 m and dune volume of $9\,m^3\,m^{-1}$ may have been sufficient to retain the elevated water levels and waves and prevent the extensive flooding that occurred at that site. Such information could have prompted authorities to undertake low-cost emergency actions in the form of artificial dune constructions based on the appropriate dune designs. While further testing of this approach is needed, the encouraging results demonstrated here point towards a new coastal management tool based on real-time forecasts that could help minimize the impacts of coastal storms in Emilia-Romagna and ultimately lead to more resilient coastal communities.

6   Conclusions

Early warning systems for dunes and sandy barrier coastlines are still in their infancy and hence require a careful assessment of their forecast performance. This study has presented one of only several such state-of-the-art systems currently operational worldwide that has been developed for the low-lying vulnerable coastline of Emilia-Romagna on the Adriatic Sea, Northern Italy. The aim of the study was to reanalyse this system for the 2012 "Halloween" storm that occurred just one month prior to the system's roll out and to ascertain to what extent the forecasts may have helped minimize the subsequent widespread flooding that occurred.

The results indicate that had this system been operational one day prior to this major storm, a high hazard "code red" forecast would have been issued for only two of the eight forecast sites, with the remaining six sites mistakenly issuing low hazard forecasts. Careful inspection of these results indicate that the main reason for these low hazard forecasts was the significant underestimation of the extreme water levels observed for this particular event. Had the model chain forecast water levels in line with measured values, a high hazard forecast would have been issued for all eight forecast sites. The results also indicate the importance of undertaking an extensive calibration of the XBeach model parameters, since considerable improvements were observed when using an optimized parameter set compared to default values.

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Despite the limitations of the early warning system for this particular event, the study highlights the overall benefits of an early warning system for a vulnerable coastline such as Emilia-Romagna. A series of what-if scenarios with regards to the emergency construction of artificial dunes illustrates that had accurate forecasts been available at the time, the rapid construction of these artificial dunes could potentially have withstood the elevated waves and water levels and significantly reduced storm damage. Current development efforts are focused on reducing the forecast uncertainties of this operational system through continued coastal monitoring, numerical model improvements and further performance assessments.

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Table 1. Summary of the eight different sites incorporated into the Emilia-Romagna Early Warning System.

Site	No. of profiles	Storm impact indicator	Grain size (µm)	Topographic dataset	Max. elevation(s) (m, range)	Dry beach width(s) (m, range)
Lido di Volano	2	BWD	150	Mar 2010 Lidar	1.5–2.6*	53–102
Lido di Spina	1	BWD	230	Mar 2010 Lidar	1.7	160
Marina Romea	1	SCW	220	Mar 2010 Lidar	4.52	28
Lido di Classe	11	SCW	200	Sep 2012 RTK-GPS	2.1–3.9	21–34
Milano Marittima	2	BWD	190	Mar 2010 Lidar	2.25*	29–40
Cesenatico	2	BWD	120	Mar 2010 Lidar	2.4*–3.0*	60–147
Rimini	1	BWD	150	Mar 2010 Lidar	1.5	124
Riccione	2	BWD	170	Mar 2010 Lidar	2.7*–3.2*	58–73

* denotes presence of artificial dunes in topographic data.

Table 2. Results of minimum Safe Corridor Width and change in sub-aerial beach volume (ΔV) predictions for the DF, PO and CX forecast modes. Values in brackets denote deviations from measured values. CO and OW refer to the Collision and Overwash Regimes, according to the four dune impact regimes described by Sallenger (2000).

Profile	Sallenger regime	Minimum SCW (m)				ΔV (m^3 m^{-1})			
		Measured	DF mode	PO mode	CX mode[a]	Measured	DF mode	PO mode	CX mode[a]
classe01	CO	−9	−1 (−8)	−19 (+12)	−7 (−2)	1	16 (+15)	51 (+35)	13 (+12)
classe02	CO	−10	−3 (−7)	−20 (+10)	−9 (−1)	9	16 (+7)	48 (+39)	18 (+9)
classe03	CO	−8	−5 (−3)	−46 (+38)	−10 (+2)	3	17 (+14)	55 (+52)	13 (+10)
classe04	CO	−8	−2 (−6)	−44 (+36)	−7 (−1)	4	15 (+11)	64 (+59)	12 (+8)
classe05	CO	−5	−3 (−2)	−36 (+31)	−6 (+1)	6	11 (+5)	55 (+49)	8 (+2)
classe06	CO	−6	−5 (−1)	−89 (+79)	−10 (+4)	0	16 (+16)	76 (+76)	14 (+14)
classe07	CO	−5	−3 (−3)	−63 (+55)	−8 (+3)	6	14 (+8)	57 (+51)	11 (+5)
classe08	CO	−7	−4 (−3)	−16 (+9)	−7 (0)	9	11 (+2)	43 (+34)	6 (−3)
classe09	CO	−6	−2 (−4)	−86 (+80)	−6 (0)	8	14 (+6)	73 (+65)	11 (+3)
classe10	OW	−11	−3 (−8)	−82 (+71)	−82 (+71)	2	11 (+9)	80 (+78)	50 (+48)
classe11	OW	−26	2 (−28)	−79 (+53)	−79 (+53)	8	8 (0)	76 (+68)	26 (+18)
Average[b]	n/a	−7	−3 (−4)	−47 (+40)	−8 (+1)	5	14 (+9)	58 (+53)	12 (+7)

[a] Optimum XBeach parameters: smax = 0.8, gamma = 0.42, eps = 0.1, facua = 0.15.
[b] Excluding overwash regime profiles *classe10* and *classe11*.

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Table 3. Results of the eight different dune configurations tested at Rimini for the what-if scenario analysis. X_{crest}, Z_{crest} and W_{crest} refer to the cross-shore position, elevation and width of the artificial dune crest respectively and V_{dune} the dune volume per alongshore meter.

Dune	X_{crest} (m)	Z_{crest} (m)	W_{crest} (m)	V_{dune} (m)	Min BWD (m)	Risk level	Percentage dune remaining (%)
Dune 1	15	1.5	20	4	0	High	47
Dune 2	15	2.0	14	11	30	Low	115
Dune 3	15	2.5	6	11	25	Low	108
Dune 4	15	3.0	2	11	23	Low	114
Dune 5	55	1.5	20	0.5	0	High	17
Dune 6	55	2.0	14	9	70	Low	87
Dune 7	55	2.5	6	9	64	Low	97
Dune 8	55	3.0	2	9	62	Low	93
No dune	n/a	n/a	n/a	n/a	0	High	n/a
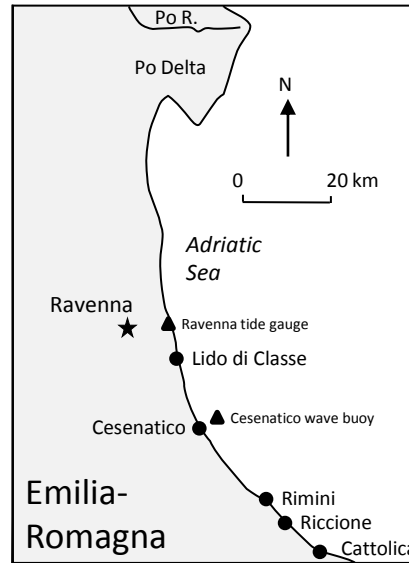
Figure 1. Map of the Emilia-Romagna region in Northern Italy.
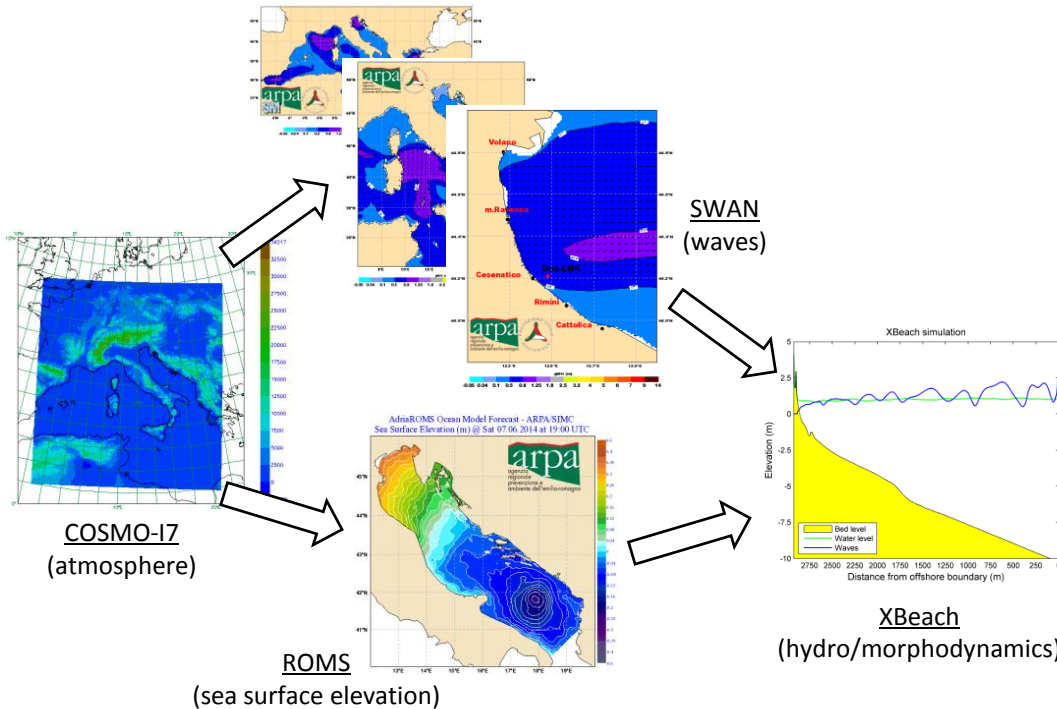
Figure 2. The Emilia-Romagna early warning system model chain: wind and pressure fields are forecast using the atmospheric model COSMO-I7, which are then used to force the ocean model ROMS and wave model SWAN. Nearshore hydro/morphodynamics are then simulated using XBeach.

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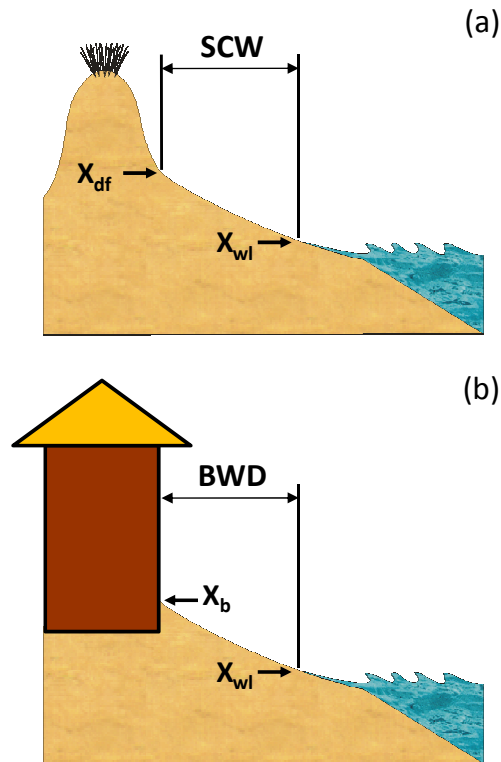
Figure 3. The two Storm Impact Indicators (SIIs) used to translate XBeach model output into a format useful for decision makers. **(a)** The Safe Corridor Width (SCW). **(b)** The Building-Waterline Distance (BWD).

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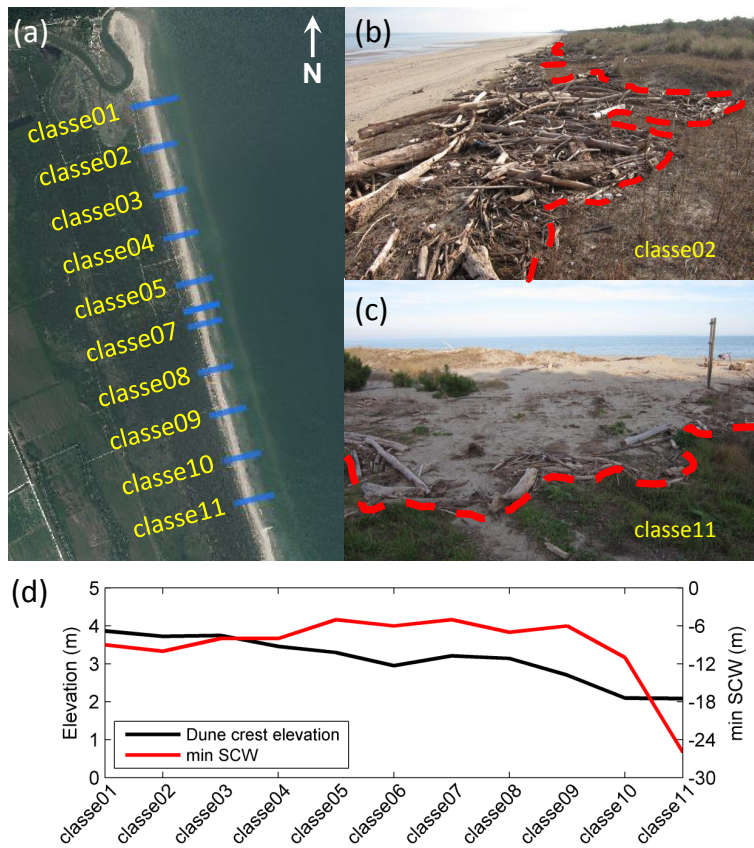
Figure 4. The Lido di Classe validation site. **(a)** Locations of all eleven profiles that are regularly monitored using RTK-GPS. **(b)** Profile line *classe02* after the Halloween storm. **(c)** Profile line *classe11* after the Halloween storm, indicating an overwash fan (Photos: Mitchell Harley). **(d)** The relationship between dune crest elevation and the minimum Safe Corridor Width (SCW) measured after the storm.
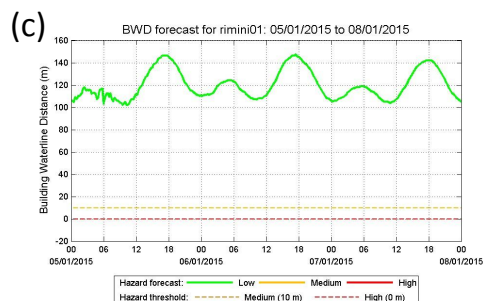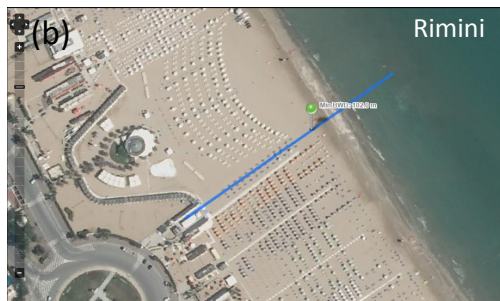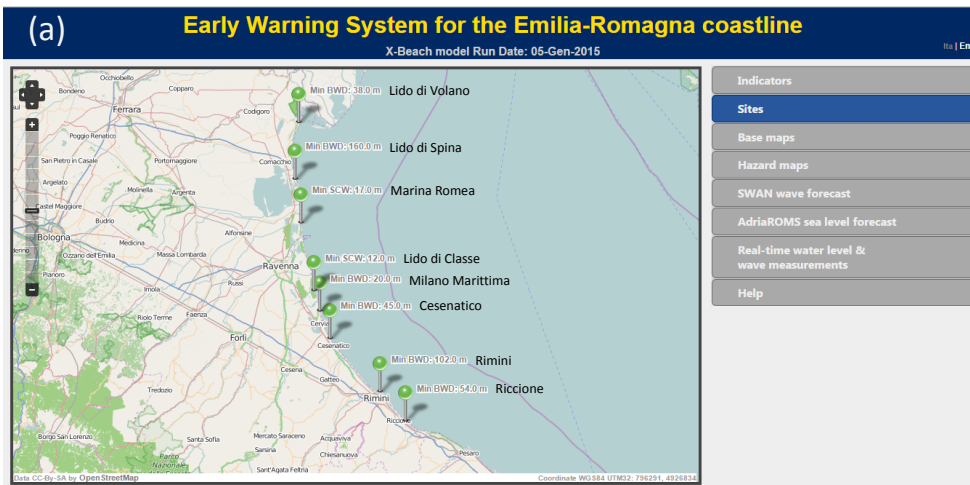
Figure 5. The Emilia-Romagna early warning system WebGIS. **(a)** A daily representation of the current coastal hazard state at all eight sites is displayed, with pin colors corresponding to the forecast hazard level. **(b)** A close up of the Rimini profile line, with the pin position indicating the forecast maximum waterline position for the following three days. **(c)** The corresponding time-series of the Building-Waterline Distance for the following three days.
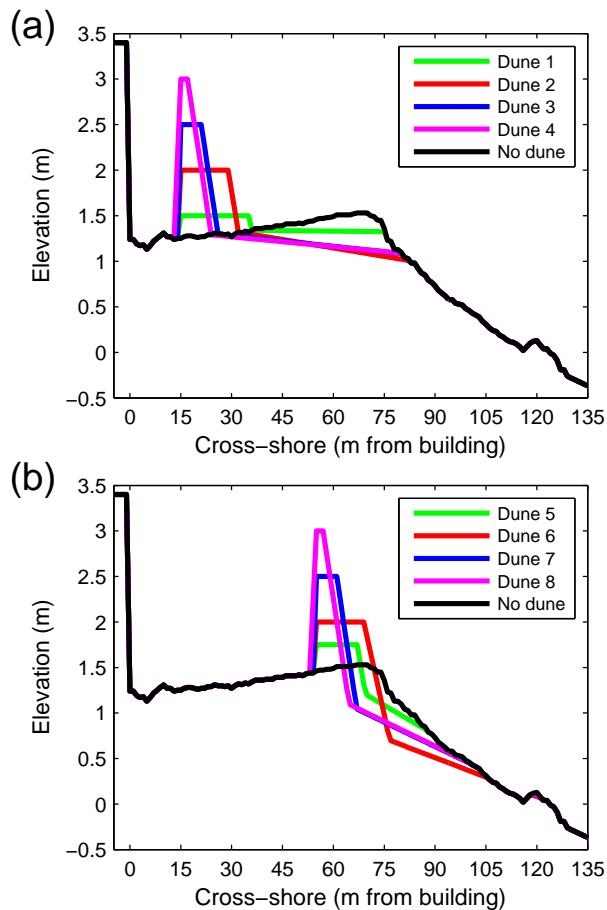
Figure 6. Dune configurations tested for the what-if scenarios at the site of Rimini. **(a)** Dune configurations 1–4. **(b)** Dune configurations 5–8. All configurations were generated using the DuneMaker software (Harley, 2014).
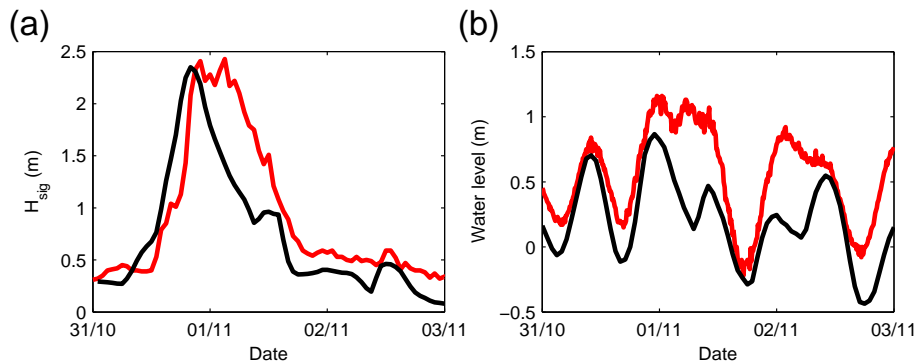
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Figure 7. Co-located measured (red lines) and three-day forecast (black lines) wave and water-level conditions for 31 October 2012. **(a)** Significant wave height. **(b)** Water level. Wave and water-level data are derived from the Cesenatico wave buoy and Ravenna tide gauge respectively.

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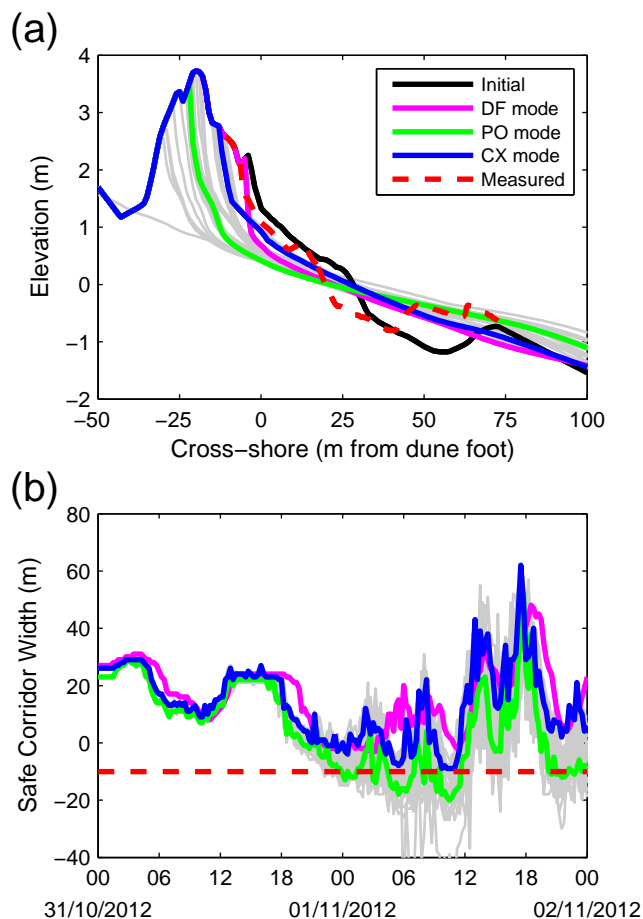
Figure 8. Forecast results at profile line *classe02* at the Lido di Classe validation site: **(a)** profile change forecasts; **(b)** Safe Corridor Width forecasts. Grey lines correspond to the 32 different model runs undertaken during the calibration process.

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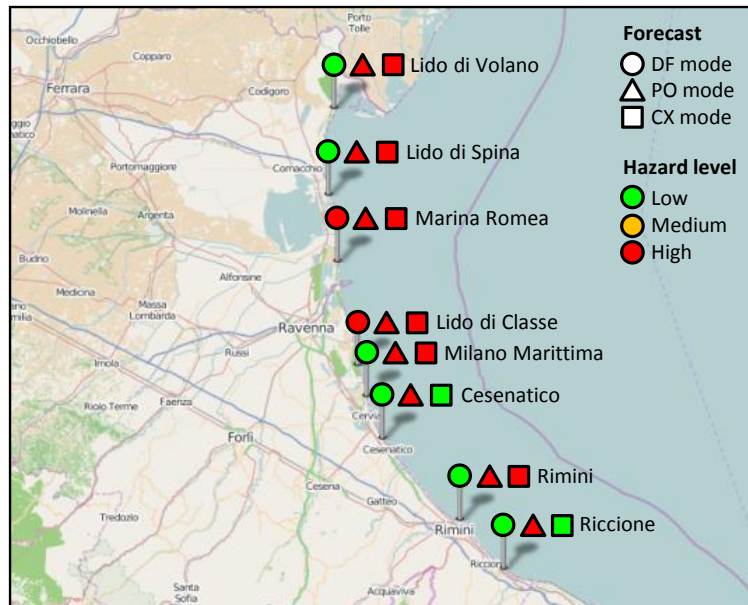
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Figure 9. Summary of forecast hazard levels at the eight early warning system sites for the three different reanalysis modes.