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An impact-oriented Early Warning and Bayesian-based Decision Support System for flood risks in Zeebrugge harbour

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ABSTRACT

Early Warning Systems (EWS) are nowadays becoming fairly standard in river flood forecasting or in large scale hydro-meteorological predictions. For complex coastal morphodynamic problems or in the vicinity of complex coastal structures, such as harbours, EWS are much less used because they are both technically and computationally still very challenging. To advance beyond the state-of-the-art, the EU FP7 project RISC-KIT (www.risc-kit.eu) is developing prototype EWS which address specifically these topics. This paper describes the prototype EWS which has been developed for the case study site of the harbour of Zeebrugge, situated in Flanders along the Belgian coast, allowing the validation of the newly developed tools. The challenge for this EWS and DSS (Decision Support System) is selecting the right number, type, and detail of the models in order to get a sufficiently detailed and trustable results, while keeping calculation time limited in order to allow fast and frequent predictions.

In general, waves inside harbours are a combination of locally generated wind waves and offshore wave penetration at the port entrance. Outside a prediction environment, the conditions inside the harbour could be assessed by superimposing processes. The assessment can be carried out by using a combination of a spectral wave model (i.e. SWAN) for the wind generated waves and a Boussinesq type wave model (i.e. Mike 21 BW) for the offshore wave penetration. Finally, a 2D hydrodynamic model (i.e. TELEMAC) can be used to simulate the overland flooding inside the port facilities.

To reproduce these processes under a EWS environment, an additional challenge is to cope with the limitations of the calculation times. This is especially true with the Boussinesq model. A model train that integrates process-based modelling, for wind generated waves, with a smart simplification of the Boussinesq model for the wave penetration effects, is proposed. These wave conditions together with the extreme water levels (including storm surge) can then be used to simulate the overtopping/overflow behaviour for the quays. Finally, the hydrodynamic model TELEMAC is run for the inundations inside the port facilities. The complete model train was integrated into the Deltares Delft-FEWS software for scenario simulating to showcase the potential for real time operations.

1. Introduction

Europe has an approximately 185,000 km long diverse coastline of large coastal cities, harbours, pristine natural habitats, sandy beaches, rocky cliffs, enclosed sea basins and exposed oceanic coastlines (Haerens et al., 2012). Storms in the past, like the storm surge event of 1953, and more recent storms, like the 2009 'Klaus' storm in the Mediterranean Sea (Ciavola et al., 2011), the 2010 'Xynthia' storm on the west coast of France (Kolen et al., 2013), the 2013/14 series of winter storms in the UK (Slingo et al., 2014), the 2013 'Xaver' or 'Sinterklaas' storm across the North Sea (Spencer et al., 2015) generating impacts on the Belgian coast, have demonstrated the vulnerability of the European coastline and the limitations of the established Disaster Risk Reduction (DRR) measures.

In Flanders, Belgium, the predicted water level of the December 2013 storm (referenced to as the 'Sinterklaas' storm, because it has coincide with the date of the annual Saint Nicholas celebration) corresponded with a 1:50 per year storm flood, the highest water level recorded since 1953 (Flikweert et al., 2015), combined with significant wave-heights of up to 2.7 m, which have a return period on the order of 1 year at the Belgian coast (Lanckriet et al., 2015a, 2015b). Although a direct comparison of 2013 water levels with the 1953 event is difficult due to a lack of 1953 data (Wadey et al., 2015), it is clear that the disaster preparedness and emergency response much improved since 1953 and that the flood impacts of the 'Sinterklaas' storm were mostly prevented through

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excellent forecasting lead times in combination with much enhanced protection measures and additional local scale flood risk management measures such as evacuation and the deployment of temporary barriers. Key learning points for Flanders after the 'Sinterklaas' storm were of a twofold character (Flikweert et al., 2015), firstly the value of the protection strategies was demonstrated, and secondly the forecasting and response during the storm was very successful.

Early Warning Systems (EWSs) are a major element in disaster risk reduction (see, e.g. Lavell et al., 2012), as disaster-preparedness plays a pivotal role in that. This has been corroborated during recent storm events. Additional local scale risk management, such as evacuation or the deployment of temporary barriers as implemented in Flanders during the 'Sinterklaas' storm, is required due to the existence of 'residual' disaster risk that ongoing disaster risk reduction processes have not mitigated or reduced sufficiently, or eliminated or prevented completely (see e.g. IDB, 2007). Also those shall be integrated into an Early Warning System.

An early warning is the provision of timely and effective information, through identified institutions, that allows individuals exposed to hazard to take action to avoid or reduce their risk and prepare for effective response, and is the integration of four main elements, risk knowledge, monitoring and predicting, disseminating information, and response (United Nations, 2006). Early Warning Systems for river flood forecasting (see, e.g., Grijsen et al., 1992; Basha et al., 2008; Krzhizhanovskaya et al., 2011; Shiravale et al., 2015) or in large scale hydro-meteorological predictions (see, e.g., Alfieri et al., 2014; Pulwarty and Sivakumar, 2014; van den Hurk et al., 2016) are becoming fairly standard nowadays. There are already successfully operational EWSs for river flooding, tsunami occurrence, hurricanes, but not yet widespread used for coastal hazards (Haerens et al., 2012). For exposed coasts the complex morphological and morphodynamic processes involved start to play an important role, making it difficult to predict short- and long-term potential risks associated with natural and human induced coastal hazards. For instance, waves and currents interact with beach and dune sediments to dissipate wave energy and act as a natural defence against storm surge (Harley et al., 2016). Inside harbours, the numerous and various types of structures add complex reflective and dissipative processes to the wave transformations. State-of-the-art EWSs for coastal storm hazards that include both hydrodynamic and morphodynamic processes have begun to recently emerge in both the USA (CoSMoS, see e.g. Barnard et al., 2014) and Europe (MICORE project, see e.g. Ciavola et al., 2011; Harley et al., 2016). Also the EU FP7 project RISC-KIT (www.risc-kit.eu) is developing prototype Early Warning and Bayesian-based Decision Support Systems (EWS/DSS) in a number of case study sites across Europe, which address the technically and computationally very challenging complex hydrodynamic and morphodynamic processes associated with natural and human induced coastal hazards, and relate them to possible impacts and/or risks.

This paper investigates whether the proposed RISC-KIT hotspot tool can be applied to harbour environments as: *(i)* a EWS for the current situation and historic low-frequency and high-impact storm events and/or synthetic events; *(ii)* a predictor of potential future effects of climate change; *(iii)* an evaluator of the effectiveness of DRR measures. Apart from the validation of the newly developed tools for a port environment, the main research question answered in this paper is which number, type, and level of detail of models should be included in the EWS/DSS in order to get a sufficiently detailed and trustable results, while keeping calculation time limited in order to allow fast and frequent predictions.

This paper describes and discusses the developed impact-oriented Early Warning and Bayesian-based Decision Support System (EWS/DSS) for the harbour of Zeebrugge, which is one of the case study sites of the RISC-KIT project. The EWS relies on process-based model simulations from a set of models running sequentially in a model train, and the Bayesian DSS is trained with those results.

2. Description of the case study site

The case study site of RISC-KIT in Belgium comprises the harbour of Zeebrugge (Fig. 1), situated in Flanders along the Belgian coast, which is located at the southern part of the North Sea between The Netherlands and France. The harbour of Zeebrugge is crucial for facilitating trade and brings significant economic benefits for the country.

As a result of a large-scale development of Zeebrugge as a deep-sea harbour, which took place in the seventies and eighties, the harbour is structured around three major parts (Port of Zeebrugge, 2016): the outer harbour, the inner harbour, and the harbour of Brugge. Only the outer harbour is considered in the present study. The outer harbour has been constructed on land reclaimed from the sea and is protected by two breakwaters having each a length of more than 4 km (Port of Zeebrugge, 2016, see Fig. 1b). Because of the direct access to the sea and the substantial water depth the outer harbour is appropriate for the fast roll-on/roll-off and container traffic. LNG (Liquefied Natural Gas) vessels also moor in the outer harbour. To pass to the inner harbour, vessels can sail via the Pierre Vandamme lock (1985) or the Visart lock (1905). Vessels

A B

Fig. 1. Location of the case study site. A: Belgian coast and harbour of Zeebrugge (inset); B: Outer harbour of Zeebrugge (source: ©Google earth).

berthed in the outer harbour do not pass through the locks. To the harbour of Brugge and back (Brugge-Zeebrugge) the ships sail via the Boudewijn canal. The terrains in the outer harbour area are also used for breakbulk handling terminals, infrastructure (roads, railways, natural gas pipeline, etc.) and residential houses (Fig. 2) in the old town of Zeebrugge.

According to Vlaamse Hydrografie (2015), the astronomical tidal range in the harbour of Zeebrugge varies between +4.58 m TAW (Mean High Water Spring, MHWS) and +0.28 m TAW (Mean Low Water Spring, MLWS) with TAW the “De Tweede Algemene Waterpassing” which is the reference height for vertical levels in Belgium. Mean Sea Level (MSL) is +2.30 m TAW. The design conditions of the two outer breakwaters are 1 in 500 year return period, 6.20 m significant wave-height, 9 s peak wave period, and +6.75 m TAW water level (Troch et al., 2004). A tidal current with a maximum velocity at spring tide of 1.80 m/s is present in front of the breakwaters (Troch et al., 1998).

The two long outer breakwaters (Fig. 1b) provide shelter to the quays and docks for large incoming waves; however, under severe storm conditions with large tides and extreme storm surge values combined and large offshore wave-heights, penetrating waves are still important and might be a threat to people working at the terminals, handling operations and port infrastructure. Further, flooding of the hinterland areas associated with high overtopping water discharges during very extreme conditions can result in losses of, inter alia, life and economic goods.

Physical processes which have an impact on the wave climate inside the outer harbour are diffraction of waves at the harbour entrance and quay walls inside the harbour, refraction and shoaling of waves propagating in shallow water and due to the presence of the navigation channel, wave reflection against different type of structures and locally generated wind waves. As such, the prediction of the potential risks associated with coastal hazards, mostly flooding, inside the harbour is typically complex and challenging, due to this complexity there is a need to couple different types of numerical models in a model train for the correct representation of all the different physical processes involved. The model train set-up used to simulate the flooding at the hinterland areas of the harbour of Zeebrugge, including aim, configuration, output, assumptions and limitations of individual local models, and the configuration of the developed EWS for the case study site of the harbour of Zeebrugge, including scenario testing results, are discussed along the following sections.

3. The model train

The developed impact-oriented Early Warning and Bayesian-based Decision Support System (EWS/DSS) for the harbour of Zeebrugge relies on process-based model simulations from a set of models running sequentially in a model train. The input/output processes and the individual models in the model train are described in the following paragraphs.

3.1. General aspects

The model train used to simulate the hinterland flooding at the port of Zeebrugge quay's, including the interaction in terms of input/output processes (one-way coupling) between the set of models running sequentially, is presented in Fig. 3. The outputs generated by the final model step in the sequence (TELEMAC flood model of the harbour of Zeebrugge) are the maximum inundation depth and the flow velocity, which are then disseminated to the Early Warning System.

The climate conditions just outside the harbour are generated by large scale, regional models – for Belgium typically at the scale of the North Sea, that are not included in the present model train set-up, but which data is used as boundary conditions in the developed Early Warning System for the harbour of Zeebrugge. The idea is that the present EWS can be a “plug-in” in larger, existing forecasting systems. For testing this model train within RISC-KIT an in-house available continental shelf model from IMDC (for a detailed description on this model reference is made to Breugem et al., 2014) is used. For future operational use the predictions of water levels and waves just outside Zeebrugge harbour from the Flemish government could be used (Vlaamse Hydrografie, 2015).

The first modelling step of the chain is to transform the wind, wave and water level forcing at the boundaries (or port entrance) into wave characteristics inside the harbour, based on the combined output from the SWAN (TU Delft, 2016) and Mike 21 BW Boussinesq (DHI, 2016) wave models. The wave characteristics (i.e., height, period, and

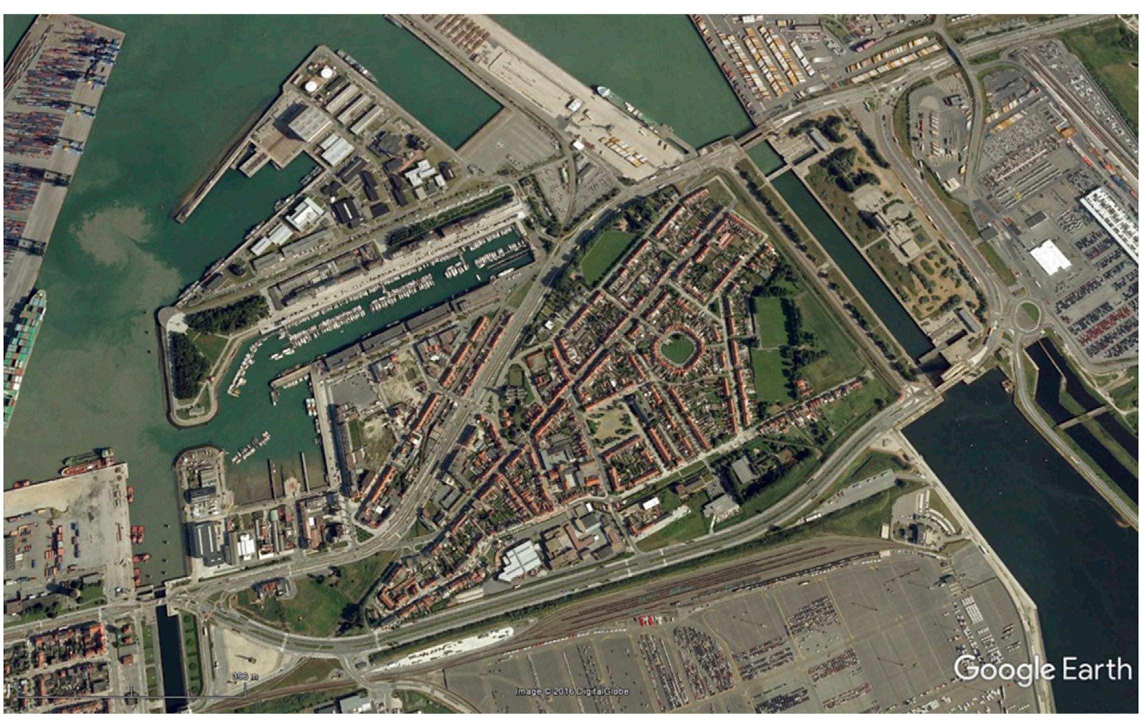

Fig. 2. Residential area, old town of Zeebrugge (source: ©Google earth).

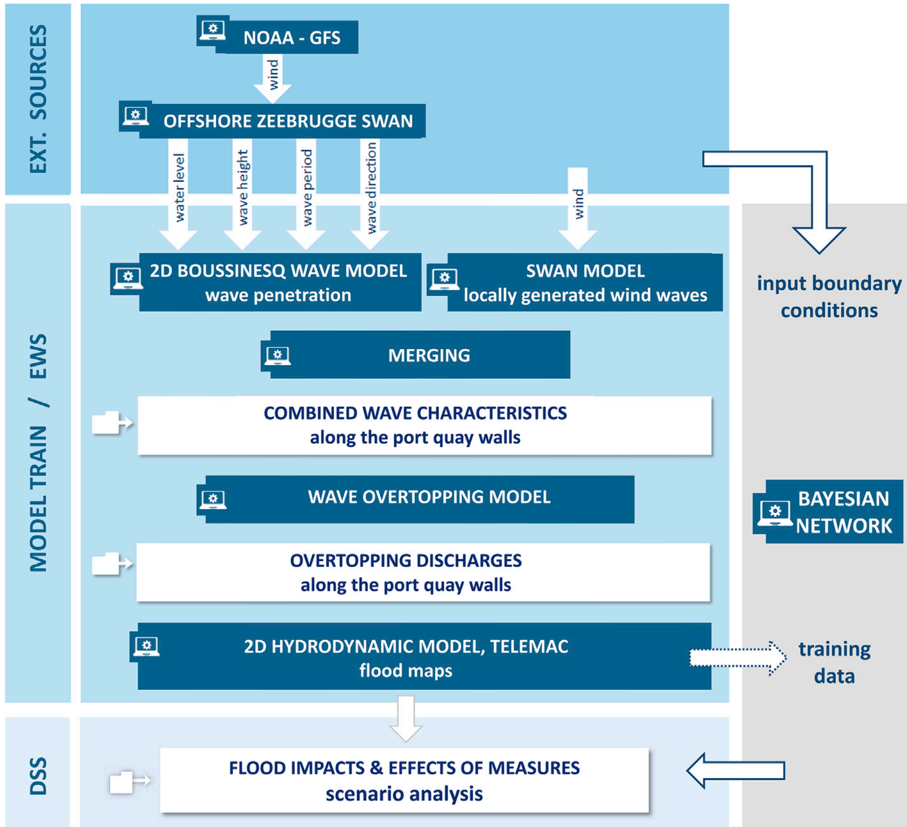

Fig. 3. Model train used to simulate the hinterland flooding at the port of Zeebrugge quays.

direction) inside the harbour, together with the water level time series and the structures' characteristics, are used to retrieve the wave overtopping discharges along the quay walls from a wave overtopping model (Pullen et al., 2007; van der Meer and Bruce, 2014). The final modelling step is to input the calculated overtopping discharges into a 2D hydrodynamic model (TELEMAC, 2016; Hervouet, 2000) to simulate the hinterland flooding at the port of Zeebrugge quay walls.

For the application within the RISC-KIT project, the model train is implemented in the Delft-FEWS software (De Kleermaeker et al., 2015). Delft-FEWS is a data centric management system with an open interface to allow easy integration of existing modelling capacities, independent of which models are used (Werner et al., 2013). A complete description and documentation of Delft-FEWS can be found on the Delft-FEWS wiki (DELTARES, 2016). All the models described earlier and discussed in more detail in the following paragraph are plugged in Delft-FEWS with specific model adapters, to ensure the correct passing of data from one model to another. Each of the EWS components is discussed more in detail within the following section.

3.2. The individual local models

The development of the wave models for accurate predictions within Zeebrugge harbour has been the subject of another research project commissioned and financed by the Flemish Government, i.e. the numerical modelling of the extreme wave climate in the Belgian harbours (Gruwez et al., 2012a). The choice of the type of models, the combination of a MIKE 21BW Boussinesq model for penetrating waves and a SWAN 2D spectral model for locally wind generated waves has extensively been investigated. The (combination of) models have been calibrated and validated with the available field measurements, and some previous physical model results for historic port configurations. Reference is made to Gruwez et al. (2012a, 2012b) for a detailed description of the model set-up, the harbour structure characteristics, and the calibration and validation results.

A SWAN 2D spectral model is used to estimate the locally generated wind waves at any location inside the port basin, using wind and water level time-series as boundary conditions. This model is 5000 by 5000 m extension, with a square mesh grid size resolution of 15 m. The size of the grid cells is optimised for the present study to reduce the calculation time and still have reliable results; on the one hand, larger grid cells results in a lower calculation time; on the other hand, smaller grid cells give a better representation of the actual wind generated waves. Especially for the smaller docks in the harbour, the results of wind generated waves is poor and unreliable in case a grid with large cells (i.e. larger than 15 m by 15 m) is considered. A sensitivity analysis to the grid size show that a 7.5 m resolution would result in only a 1% difference in results (i.e. the wave-heights). It should be noted here that only the locally generated wind waves are included in this model, i.e. no effect of penetrating waves, to allow superposition with the wave penetration computed from the 2D Boussinesq wave model, MIKE 21 BW, later in the model train sequence.

To estimate the wave penetration into the harbour of Zeebrugge, i.e. the ratio between wave-height outside and inside the port, an existing calibrated and validated 2D Boussinesq wave model, MIKE 21 BW, set up in a previous study by Gruwez et al. (2012a, 2012b), is used and adapted to investigate several possible scenarios. The same numerical grid as used by Gruwez et al. (2012a, 2012b), that is a grid cell resolution of 5.0 m by 5.0 m, is retained in the present study. The model input consists of the nearshore wave characteristics (i.e. height, period and direction) coming from a large scale SWAN model (outside the current model train as shown in Fig. 3), the water level and all harbour structure characteristics (for the reflection). All wave penetration simulations are conducted with the JONSWAP spectrum (with peakedness parameter, γ, of 3.3), which is representative for the North Sea (Hasselmann et al., 1973). The model output is a matrix of the ratio between wave-height outside and inside the port for varying water level at different locations inside the port. For the wave penetration, the wave period inside the harbour is found to be (almost) equal to the wave period outside the harbour.

A wave overtopping model (see Pullen et al., 2007; and van der Meer and Bruce, 2014) is used to calculate the overtopping discharges along the port quay walls. Model boundary conditions are the time-series of water levels and wave characteristics at the quay walls (i.e., wave characteristics for the combination of the wind waves – from SWAN, with the waves penetrating in the harbour – from Mike 21 BW), and the structures characteristics (type of structure, crest level, depth of the toe, etc.) as gathered before by Gruwez et al. (2012b) and updated where needed during the present study. The overtopping discharges along the quay walls are calculated at single points, separated from each other by 5 m. The model outputs are: (1) time series of the wave characteristics (significant wave-height, wave period from the wave energy spectrum and wave direction) along the quay walls; (2) time series of the freeboard along the quay walls; (3) time series of the average overtopping discharges along the quay walls; (4) time series of the overflow discharges along the quay walls; and (5) one time series per section of the quay wall equal to the maximum average overtopping discharge observed along the quay wall, which is used by the 2D hydrodynamic model, TELEMAC, to simulate the hinterland flooding at the port of Zeebrugge quay walls.

The final modelling step in the model train sequence is the 2D hydrodynamic model, TELEMAC (TELEMAC, 2016; and Hervouet, 2000), which is used to predict the hazard intensity (i.e., maximum inundation depth and flow velocity) at the receptors located at the hinterland behind the harbour of Zeebrugge quay walls. The 2D hydrodynamic model includes all the quays of the outer port of Zeebrugge (Fig. 4) and limited ones in the inner port to be able to model the flood dynamics realistically and to get the flooding water out of the model in a proper way. The resolution of the model mesh is 25 m (face length), which has been increased in some parts for a better consideration of the existing topography (Fig. 5). To increase the quality of the interpolation, the mesh has been forced to follow the topography and the structures (connection between the locks and the basins or the roads). The mesh contains 464,484 triangular elements (corresponding to 24,104 grid points), based on an optimisation of the computation time versus accuracy. The topography used in the model is based on the digital elevation model based on LIDAR data, surveyed in March 2014 with 5 m resolution. Additional model inputs include the time series of the overtopping discharges along the port quay walls from the wave overtopping model, and the roughness coefficients based on the type of land use. The model outputs are: (1) time series of the water level; (2) time series of the flow velocity; and (3) time series of the inundation depth, of which the maximum inundation at depth at the receptors located at the hinterland of the port of Zeebrugge quay walls is used as hazard input to the Bayesian Network.

3.3. *Wave climate in the harbour*

The wave climate in a harbour consists of two components: (1) locally generated wind waves and (2) offshore waves penetrating into the harbour through the port entrance. The two components are determined with two different models. For the locally generated wind waves a spectral wave model, i.e. SWAN, is used. For the wave penetration through the harbour entrance a Boussinesq type wave model, i.e. Mike 21 BW, is applied.

With the Boussinesq wave model, nearshore waves in front of the harbour entrance are translated into waves inside the harbour. Through the harbour entrance, waves propagate in the harbour and are diffracted around the breakwaters heads at the harbour entrance. In the harbour itself waves are diffracted around and reflected at the quay walls. Due to changes in the water levels and the presence of the navigation channel towards and inside the harbour the physical processes of wave refraction and shoaling also influence the wave climate in the harbour. The input of the model consists of the nearshore wave characteristics (i.e. wave height, period and direction), the water level and all harbour structure characteristics (for the reflection).

The Boussinesq type wave model is calculation intensive. Also the output should be carefully used and requires some interpretations. For

Fig. 4. TELEMAC model for the harbour of Zeebrugge case study site (the small black dots are the grid points of the model).

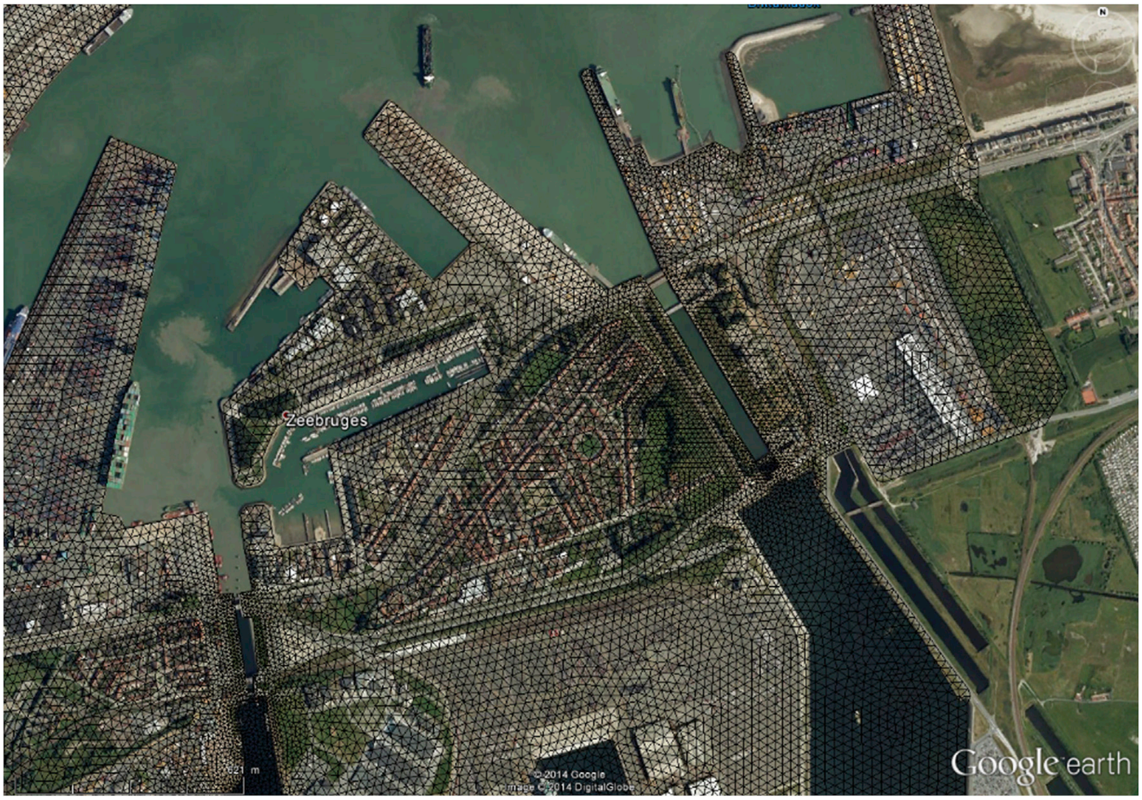

Fig. 5. Zoom in to the mesh around the old city of Zeebrugge, one of the most vulnerable inside the case study site.

example for wave overtopping calculations typically incident wave heights are required, whereas the standard model results still include the effect of reflected waves and eventually also standing waves. The interpretation of the results from the Boussinesq models has to be done individually, i.e. a critical evaluation of the results has to be made per simulation, and the final incident wave height has to be determined. This interpretation step makes it, together with the long calculation time, difficult to run the Boussinesq model directly in the model train. A simplified implementation of the Boussinesq model is therefore considered in the model train. The Boussinesq model is run on beforehand for several cases of different water levels combined with different offshore wave-heights, wave periods and different wave directions. The results of these runs are analysed and put into a matrix which links every result to a specific offshore wave-height, wave direction and water level. This matrix is used within the model train. For wave and water level combinations which are not directly present in the matrix, linear interpolation is applied.

The results of the SWAN model for the locally generated wind waves and the simplified implementation of the Boussinesq model on the wave penetration from outside to inside the harbour can be superimposed by using the formulas proposed by van der Meer et al. (2002) as follows:

$$H_{mo} = \sqrt{H_{m0\ \ wave\ penetration}{}^2 + H_{m0\ \ wind\ waves}{}^2} \quad (1)$$

$$T_p = \left(\frac{H_{m0\ wave\ penetration}}{H_{m0}}\right)^2 T_{p\ wave\ penetration} + \left(\frac{H_{m0\ wind\ waves}}{H_{m0}}\right)^2 T_{p\ wind\ waves} \quad (2)$$

where H_{m0} is the zero moment wave height and T_p is the peak period; the indices 'wave penetration' and 'wind waves' refer to the results of the Bousinesq and SWAN and wave models, accordingly. The zero moment wave height at some location along the harbour quay walls, i.e. $H_{m0\ quay\ wall}$, is estimated by

$$H_{m0\ quay\ wall} = K_d\ H_{m0\ outside\ the\ harbour} \quad (3)$$

in which K_d is the ratio between wave height inside the harbour at some location along the harbour quay walls and outside. The wave penetration peak wave period is set equal to the peak wave period outside the harbour.

The above procedure is a simplification of the real physics of the problem that could provide inaccurate predictions of the wave height distribution along the harbour quay walls, leading in turn to lower quality predictions of the overtopping discharges and consequently of the hinterland flooding predictions. That simplification is however the common practice for now. Although the wind effect on wave breaking has been demonstrated for some time now (see e.g. Douglass, 1990; and Feddersen and Veron, 2005), the work in this area is still in its infancy, with much to be done to arrive at a point in which an understanding of wind effects on the breaking process is in hand (Kirby, 2016). Some attempt has been made to add wind effects to Boussinesq-type models, beyond the simple application of a spatially uniform surface stress, by: (1) Chen et al. (2004) which model was tested against data for wave growth with fetch, and showed some skill in predicting the change in wave height, but failed to predict concurrent increase in wave period; and (2) Liu et al. (2016) which introduced a new source formulation based on a wave-induced pressure perturbation instead of wind stress, and further developed a spectral model to examine the effect of wind on nonlinear triad interaction and recurrence, but did not provide comparisons with data for the new model or provide any relative evaluation of the two formulations or any comparison of effects on local surface geometry. In-depth reviews on the development and applications of Boussinesq-type models are given by Madsen and Schäffer (1999) and Kirby (2003), and more recently by Kirby (2016).

3.4. Hinterland flooding

The wave characteristics at specific locations inside the harbour, estimated from the combination of the SWAN and the Boussinesq wave model results, together with the water level time series and the structures' characteristics (crest elevation level of the quay wall, slope, water depth at the toe of the structure, friction coefficient, etc.), are used to predict the overtopping discharges along the along the harbour quay walls. Based on the type of structure (vertical quay wall or sloped dike) as well as the crest elevation levels and the structure orientation, the harbour is divided in a number of sections (Fig. 6). It should be noted here that the presence of a berm and the width of the crest of the structure are not considered in the present demonstration model. This is possibly a slightly conservative approach as including this structure characteristic could result in a decrease of the predicted overtopping rate. Anyhow, even when all structure characteristics are fully known and considered for the overtopping predictions, the use of empirical formulas always is limited to the range of conditions, and type of wave spectra tested and considered for those formulas. Quite often, physical model tests are performed to accurately predict the overtopping discharge and to optimise the design of e.g. storm walls (Trouw et al., 2012), or to determine overtopping reduction for harbour quays under very oblique waves attack (Dan et al., 2014).

The average overtopping rate is calculated based on the formulas suggested by Pullen et al. (2007) using the specific formulas for the dike, rubble mound breakwater and vertical wall types of structures. The approach initially proposed by Pullen et al. (2007) has been updated by van der Meer and Bruce (2014) for the dike and rubble mound breakwater types of structure, in case of a relative crest freeboard smaller than 0.5 to 1.0. Where appropriate, the revised approach by (van der Meer and Bruce, 2014) is used in the present study. As per Pullen et al. (2007), a deterministic approach to estimate the overtopping discharges is followed.

The estimated overtopping discharges along the quay walls are used as an input for a 2D hydrodynamic model, i.e. TELEMAC (TELEMAC, 2016; and Hervouet, 2000), to predict the hinterland flooding.

4. Bayesian-based DSS

Bayesian Networks have been proven useful in a number of coastal applications, as for example to predict coastal hazards for sandy beaches (Poelhekke et al., 2016), cliff erosion (Hapke and Plant, 2010) and coastal vulnerability to sea level rise (Gutierrez et al., 2011), to assess the interactions between barrier island geomorphic variables (Gutierrez et al., 2015), and to relate the onshore hazard intensities to observed building damage for the case of the impact of hurricane Sandy on a part of New York (van Verseveld et al., 2015). In the present study, a Bayesian Network (BN) is used to relate offshore hydraulic boundary conditions (significant wave-height from five wave directions and peak water level, as presented in Table 1) to hinterland coastal flooding at receptors inside the harbour of Zeebrugge through a transformation using process-based model simulations. The BN will act as a surrogate for all the implemented numerical models in the model train. The principles of the BN approach for these kind of applications is described in Jäger et al. (2017). The basic set-up of the BN for the coastal flooding of the town of Zeebrugge has been discussed in Jäger et al. (2015). For the present case study the study area has been extended towards the entire outer harbour of Zeebrugge, including the first line of flood defence towards the hinterland, and a BN has been set up according to the same principles.

The data used in the Bayesian Network training is based on results from a total of 615 simulations of selected scenarios comprising of: (1) synthetic events up to a return period of 4000 years, under current climate conditions; (2) climate change scenarios (CCS) with projections

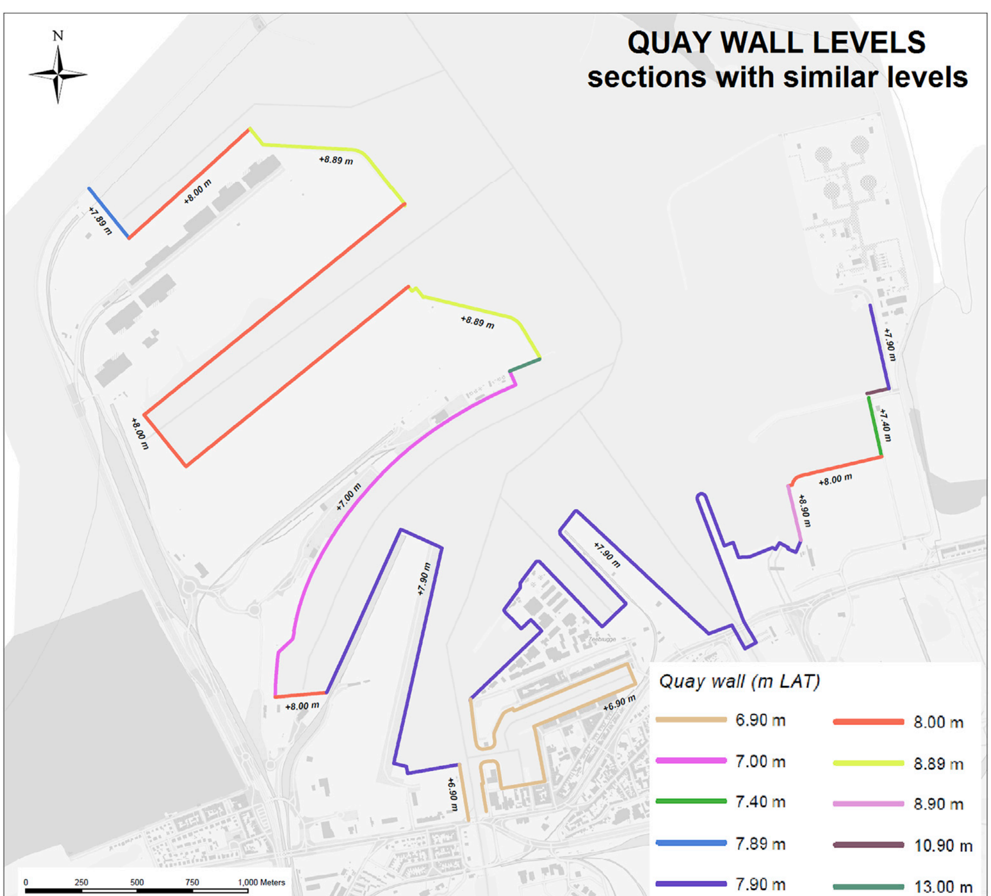

Fig. 6. Wave overtopping model for the port of Zeebrugge case study site (crest elevation levels are indicated in m TAW).

Table 1
Hazard boundary conditions for the harbour of Zeebrugge case study site.

Type	Number of simulations	Range of training data	
		Significant Wave-height [m]	Peak Water-level [m TAW]
Synthetic	135	0.5–6.5[1]	4.75–6.75
DRR (modelled)	410	0.5–6.5[1]	4.75–7.75
CCS	70	0.5–6.5[1]	7.25–7.75

[1]Simulated wave directions: 0°N, 45°N, 90°N, 270°N and 315°N.

of extreme storm surge and relative sea level rise under the Representative Concentration Pathway RCP8.5 during this century, RCP8.5$_{2060}$ and RCP8.5$_{2100}$ to be more specific; and (3) current and future predicted climate conditions with hazard and vulnerability/exposure influencing Disaster Risk Reduction (DRR) measures and Strategic Alternatives (SAs) being implemented.

As shown in Table 1, the peak water level (incl. the storm surge) ranged from 4.75 to 7.75 m TAW (divided into classes of 0.5 m), the significant wave height has been varied from 0.5 to 6.5 m (divided into classes of 0,5 m), and all wave directions generating penetrating waves in the harbour have been included, i.e. West to East (270, 315, 0, 45, 90°N; classes of 45°). For each combination of significant wave-height, wave direction and peak water level a 46 h storm is simulated, which corresponds to three high-tides. A total number of 205 conditions have been chosen, with a focus on the conditions that generate flood impacts, to run the simulations under current and future predicted climates, earlier described scenarios (1) and (2). The same number of model runs have been performed with each one of the proposed DRR hazard influencing measures, i.e. ‘Master Plan for Coastal Safety’ and ‘Mobile flood barriers’, implemented, earlier described scenario (3). This number of selected model runs provided enough information to train the BN to predict the flood impacts of any realistically occurring event. The performance of the BN can be further improved by adding more simulation results with for instance different water levels, wave heights and directions, and/or varying the secondary parameters such as wave period, storm duration, etc.

It should be noted here that, to be consistent with what has been used in the development of the Integrated Master Plan for Coastal Safety (Afdeling Kust, 2016), it was decided to use only synthetic events with known return period in this study. The few historical events for which

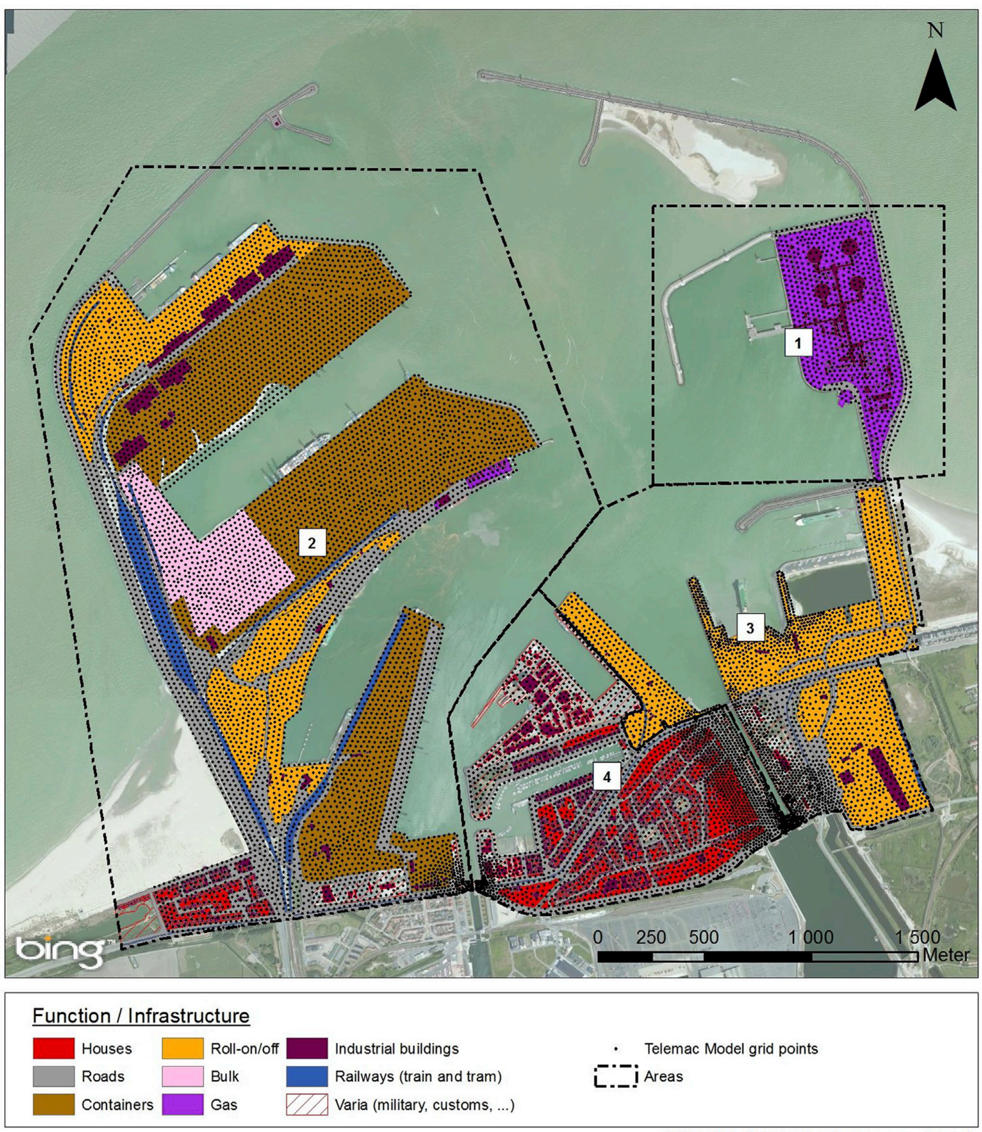

Fig. 7. Areas and individual receptors.

time series are available (e.g., the storm of 1953, and the Xaver storm of 2013) have return periods well below the safety level of the Master Plan for Coastal Safety. The conditions observed during those storms are within the combination matrix chosen for the synthetic events. The projections in extreme total water levels, due to relative sea level rise and extreme storm surge levels during this century under RCP8.5, used in the present study, are in agreement with the conclusions of Vousdoukas et al. (2016) from the Joint Research Centre, Institute of Environment and Sustainability, European Commission, which dataset is publicly available from EC Joint Research Centre (2016).

The Bayesian Network set-up is built around a structure linking hazard intensities and impacts, in which five categories of variables can be distinguished: hazard boundary conditions, receptors, local hazards, impacts, and DRR measures and Strategic Alternatives. Within each category, a number of nodes (e.g. peak water level and significant wave height in the hazard boundary conditions variable category, or the maximum inundation depth in the impacts variable category) is included. The definition of the nodes in the receptors category is based on a division of the hinterland areas of the harbour of Zeebrugge in 4 distinct areas (Fig. 7), which are then further divided into different receptors based on port functions allowing the assessment of the impact of flooding on each of those functions. In addition to that, the potential disruption to the road network and to public transportation (train and tram networks) can be analysed as they are included in the network as individual receptors; furthermore, the potential damage to the houses in the residential areas at the old town of Zeebrugge can also be studied.

The maximum inundation depth at each receptor is assessed by linking their spatial distribution to the local hazard intensities computed with the numerical models; no other hazard impacts are relevant in this case study area. The coastal flooding hazard impact on the hinterland is assessed in terms of the maximum inundation depth, which is then related to the percentage of damage by means of a depth-damage curve. For the Zeebrugge case study site a combination of depth-damage curves developed based on Flanders region site specific data by Deckers et al. (2010) and a synthetic (hypothetical) curve for cars and containers based on expert judgement (developed irrespective of site specific flood and damage survey data) is used.

A schematic overview of the BN setup for the flood impact in the harbour of Zeebrugge is shown in Fig. 8. Each of the five categories of variables (hazard boundary conditions, receptors, local hazards, impacts, and DRR measures and Strategic Alternatives) are indicated, as well as the links between them.

As an example and to test the approach, two hazard influencing DRR measures (see Fig. 9), 'Master Plan for Coastal Safety' (DRR1) and 'mobile flood barriers' (DRR2), and one vulnerability/exposure DRR measure, 'moving assets out of risk', have been implemented in the present scenario testing:

1) 'Master Plan for Coastal Safety' (DRR1), affecting the hazard intensity of mostly the 'Houses' receptors in area 4 (see Fig. 7), which is a measure foreseen in the Integrated Master Plan for Flanders Coastal Safety (Afdeling Kust, 2016) and which consists of the placement of a storm wall built to a crest level height of +8 m TAW, with direct impact on the flooding hazard impact at the old town of Zeebrugge; because it is a hazard influencing DRR measure additional modelling efforts to simulate its effect were required;
2) 'Mobile flood barriers' (DRR2), which consists of the strategic placement of (heavy) containers as flood barriers in vulnerable locations within both the Container handling and Roll-on/off terminals in Area 2 (see Fig. 7), and which partly coincide with the porous wall build with Haro blocks, currently present on-site to limit spray effects; and
3) 'Moving assets out of risk' (DRR3), which implementation requires pre-event action (assumed operation and uptake factors together is 50%, for more detail see Cumiskey et al. (2016) and consists of raising the floor height of the containers or moving them from the flood-exposed areas to less risky ones in the case of assets at the Container handling terminals in area 1 (see Fig. 7), and moving cars from the flood hazard zones at the Roll-on/off terminals in areas 2 and 3 (see Fig. 7).

Hereafter some selected results are discussed for DRR measures 1 and 2, as an example of the capabilities of the BN approach for scenario analysis. As explained above, the hydrodynamic model has been re-run with two new configurations (T1 and T2), consisting of the two different hazard influencing DRR measures. All those results have been integrated in the BN. Fig. 10 shows, for one specific storm condition (5.5 m significant wave-height and 7.25 m peak water-level), an example of the obtained flood inundation map for the cases where no DRR

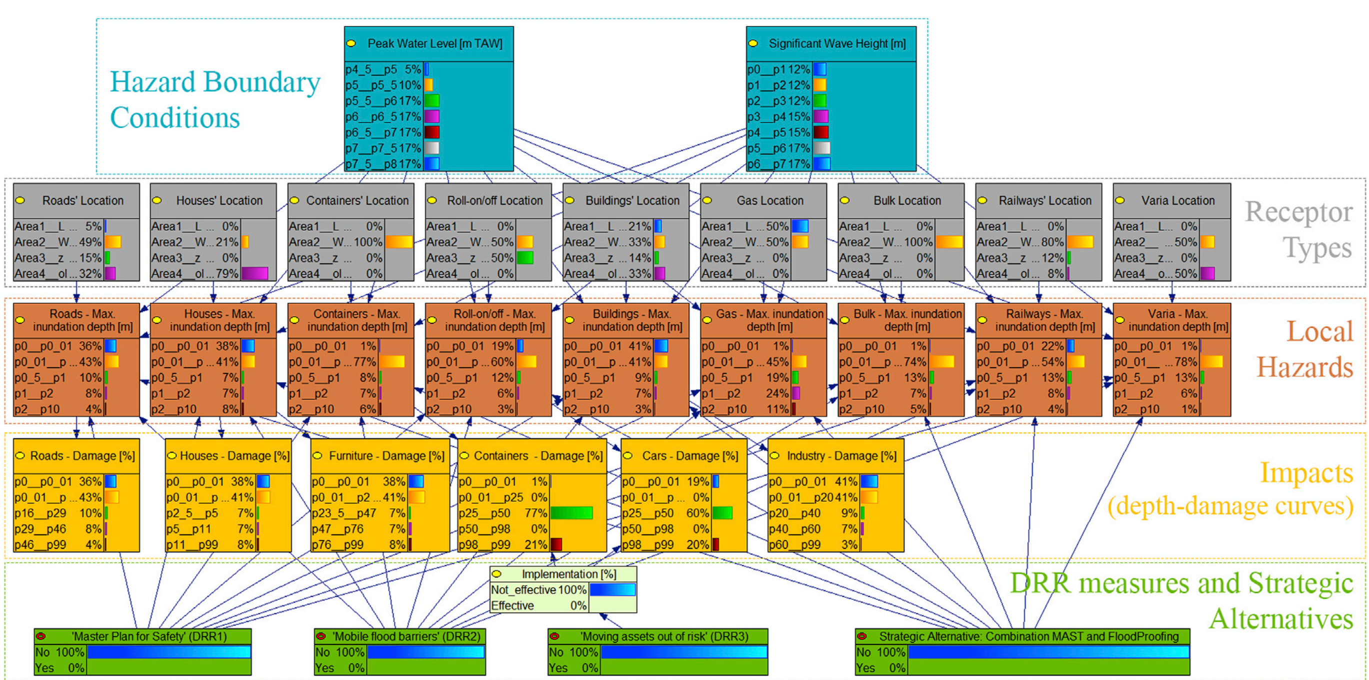

Fig. 8. Schematic overview of the BN for the flood impact in the harbour of Zeebrugge.

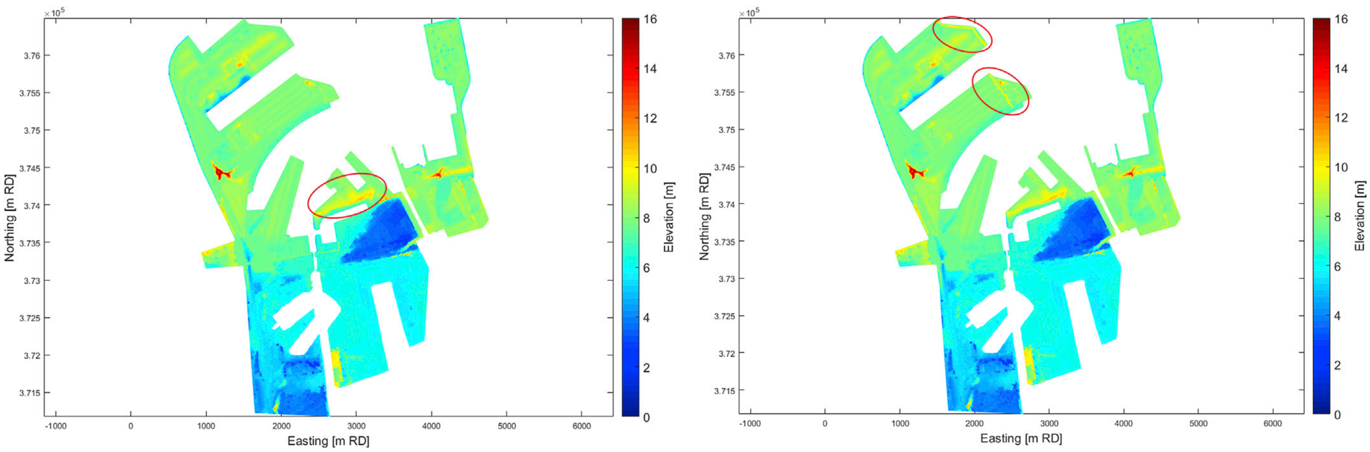

Fig. 9. Location (circled in red) of the DRR measures per configuration: DRR1 and DRR2, on top of the topography (ranging from 0 till 16 m TAW). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

measure is implemented (Fig. 10, left panel) and where there is a DRR measure 2 is implemented (Fig. 10, right panel).

Table 2 shows selected output of the BN, in this case the probability distribution of the coastal flood inundation hazard for the selected receptors ‘Houses’ in area 4 (see Fig. 7), and ‘Containers’ and ‘Roll-on/off’ in area 2 (see Fig. 7) for all simulated storm conditions, including climate change. Figures in Table 2 show that when the DRR measures are implemented there is an overall slight (below 5%) decrease in the probability distribution of the predicted inundation depth for the higher bin classes (above 0.5 m water depth), with consequent increase of the lower ones. For instance, 54% of the ‘Houses’ in area 4 are expected to be inundated up to 0.5 m at the present condition (including climate change), whereas with the DRR1 measure implemented, this is only 49%. Similar conclusion can be drawn for the receptor ‘Containers’ in area 2, however for the ‘Roll-on/off’ in area 2 the risk is not reduced with the implemented DRR2 measure. It should however be pointed out that the DRR2 measure was only implemented in part of the ‘Roll-on/off’ situated in area 2, i.e. at the northernmost quay-wall, which means that more and different locations can be tested so to improve the effectiveness of this DRR measure.

5. Discussion

The EWS/DSS developed for the harbour of Zeebrugge has been used for scenario testing, that is as a predictor of potential effects of current and future predicted climate and as an evaluator of the effectiveness of DRR measures. It can also be used as a plug-in of larger hydro-meteorological models (e.g. Global Forecast System, European Centre for Medium-Range Weather Forecasts). By using the output of hydro-meteorological models as the input of the EWS, the storm conditions in the harbour can be forecasted and the EWS/DSS used in operational conditions. In this mode, the EWS/DSS can be used to inform port authorities and companies active in the harbour to prepare themselves for an upcoming extreme event. Such preparation could be an action order to move assets out of risk (tested DRR3) or to strategically place containers as flood barriers in vulnerable locations (tested DRR2). The application of the EWS/DSS in the scenario testing mode is discussed in the following.

In the scenario testing mode, the EWS/DSS was tested as a predictor of potential effects of current and future predicted climate and as an evaluator of the effectiveness of DRR measures. For the current condition (i.e. no DRR measures implemented) under both present and future predicted climate, the scenario testing showed that there are two particularly vulnerable areas to flooding from inside the harbour during very extreme events, under both current and future predicted climates, one located in the old town of Zeebrugge, and the other located at the two northernmost quay-walls at the western part of the outer port. Other receptors inside the port are more or less affected depending on the storm scenario. Based on this result, two hazard influencing DRR measures, i.e.

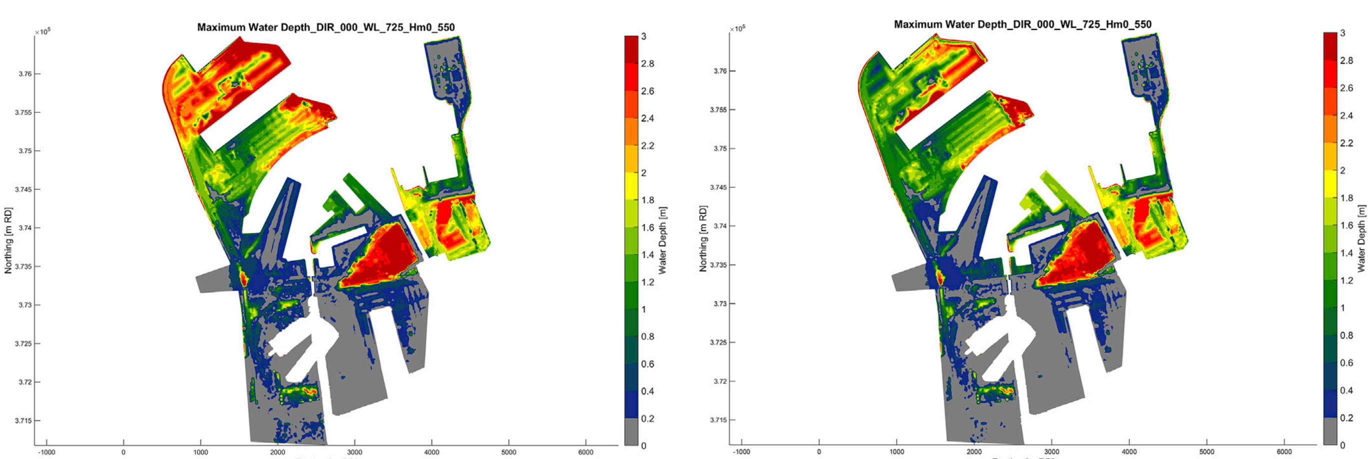

Fig. 10. Flood inundation maps for the outer port and surroundings under future predicted climate, without (left panel) and with (right panel) DRR measures implemented.

Table 2
Probability distribution from the BN of the inundation hazard for all simulated storm conditions including climate change, per selected areas and receptors, without and with DRR measures implemented.

Maximum Inundation Depth [m]	Area 4	Area 2	
	Receptor: 'Houses' without/ with DRR1	Receptor: 'Containers' without/with DRR2	Receptor: 'Roll-on/ off' without/with DRR2
0–0.01	28% / 36%	1% / 1%	1% / 1%
0.01–0.5	54% / 49%	91% / 94%	88% / 88%
0.5–1.0	7% / 6%	8% / 5%	11% / 11%
1.0–2.0	6% / 5%	0% / 0%	0% / 0%
above 2.0	5% / 4%	0% / 0%	0% / 0%

'Master Plan for Coastal Safety' and 'Receptors Flood Proofing', and one vulnerability/exposure influencing DRR measure, i.e. 'Moving assets out of risk', were selected for testing. In addition, three Strategic Alternatives (i.e. combinations of two or more DRR measures) are proposed and tested. The implementation of the DRR measures and Strategic Alternatives focus on the particularly vulnerable areas to flooding under both current and future predicted climates.

6. Conclusions

An impact-oriented Early Warning and Bayesian-based Decision Support System (EWS/DSS) has been developed for the port of Zeebrugge within the EU FP7 project RISC-KIT. The analysis presented herein focused on the application of the EWS/DSS as: *(i)* a EWS for the current situation (without DRR measures being implemented) and historic low-frequency and high-impact storm events and/or synthetic events; *(ii)* a predictor of potential future effects of climate change; *(iii)* an evaluator of the effectiveness of DRR measures.

As an Early Warning System for the current situation (without DRR measures being implemented), the Bayesian Network is able to propagate forward the relevant hydraulic boundary conditions and translate them into hazard intensities and impacts at specific receptors, which facilitates port authorities and other key stakeholders with systematic information to detect, monitor and forecast potentially hazardous events, and analyse the risks involved. The EWS capabilities of the Bayesian Network are supported by a complex suite of robust models, which can be fully integrated into the Delft-FEWS software to develop a fully operational forecasting platform. The system can be easily adapted and extended to more boundary conditions, receptors, local hazards and impacts, so to enhance disaster preparedness for effective risk reduction through better monitoring and forecasting of low-frequency, high impact hydro-meteorological events. The system is also suitable for raising stakeholder awareness of local hazards/risk. Similar findings were made for the other RISK-KIT case studies, and are discussed in the final paper of this issue (Ferreira et al., 2017).

The prediction and diagnosis values of the EWS/DSS obviously depend first and foremost on the quality and accuracy of the underlying models. As earlier explained, the model train of the EWS is implemented in the Delft-FEWS software and consists of different models which translate offshore wave conditions to hinterland flooding. Two models, one spectral wave model, i.e. SWAN, and one Boussinesq type model, i.e. MIKE21, are used to determine the waves in the harbour based on offshore wave conditions. With the wave climate in the harbour the overtopping discharges are calculated. The overtopping discharges and water levels are the input for a 2D hydrodynamic models, i.e. TELEMAC, with which the hinterland flooding inside the port facilities is calculated.

The model train of the EWS developed for the harbour can be used as a plug-in for larger hydro-meteorological models. By using the output of hydro-meteorological models as the input of the EWS, the storm conditions in the harbour can be forecasted. This can inform port authorities and companies active in the port to prepare themselves for an upcoming storm. The model train of the EWS can also be used to simulate different scenarios, e.g. specific storm conditions or to test the impact of the climate change. Based on the output, mitigation measures can be identified. The impact of the mitigation measures can also be verified by implementing them in the local topography or bathymetry of the 2D hydrodynamic model.

One of the improvements of the model train lies within the simplified implementation of the Boussinesq model. If more results of the Boussinesq model with different water levels combined with different offshore wave-heights become available, the matrix can be enlarged. This would not allow to more accurately include the different reflection and transmission coefficients of the widely different structures with varying water level, but also to increase the number of incoming wave directions, which can highly impact the local wave climate due to the interaction with the entrance channel (Gruwez et al., 2012a). A very large matrix can also be used to train a neural network. Such a neural network can then replace the matrix of the Boussinesq model and may result in a more accurate prediction of the waves penetrating in the harbour. A first attempt has been made during this study, but due to the somehow limited number of simulations with the Boussinesq model, not enough results where available to train a reliable neural network. Improvements to the 2D hydrodynamic model include more detailed topography and refined model around the most vulnerable areas and a more detailed boundary conditions. The prediction and diagnosis of the EWS/DSS could benefit as well from the inclusion of a hydrodynamic model of the harbour into the model train, so that variations of storm surge and resulting total water level inside the harbour (effect estimated to be small) could be included as well as the possibility to predict current patterns.

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