ARTICLE IN PRESS

Coastal Engineering xxx (2017) 1–12

Contents lists available at ScienceDirect

Coastal Engineering

journal homepage: www.elsevier.com/locate/coastaleng

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

Annelies Bolle *, Luciana das Neves, Steven Smets, Justine Mollaert, Saul Buitrago

International Marine and Dredging Consultants (IMDC nv), Van Immerseelstraat 66, Antwerp 2018, Belgium

ARTICLE INFO

Keywords:
Early Warning System
Delft-FEWS
SWAN
Boussinesq-type models
TELEMAC
Bayesian Network

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

* Corresponding author.
E-mail addresses: Annelies.Bolle@imdc.be (A. Bolle), ldn@imdc.be (L. das Neves), sme@imdc.be (S. Smets), jum@imdc.be (J. Mollaert), sbu@imdc.be (S. Buitrago).

https://doi.org/10.1016/j.coastaleng.2017.10.006
Received 12 January 2017; Received in revised form 15 October 2017; Accepted 16 October 2017
Available online xxxx

Please cite this article in press as: Bolle, A., et al., An impact-oriented Early Warning and Bayesian-based Decision Support System for flood risks in Zeebrugge harbour, Coastal Engineering (2017), https://doi.org/10.1016/j.coastaleng.2017.10.006

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

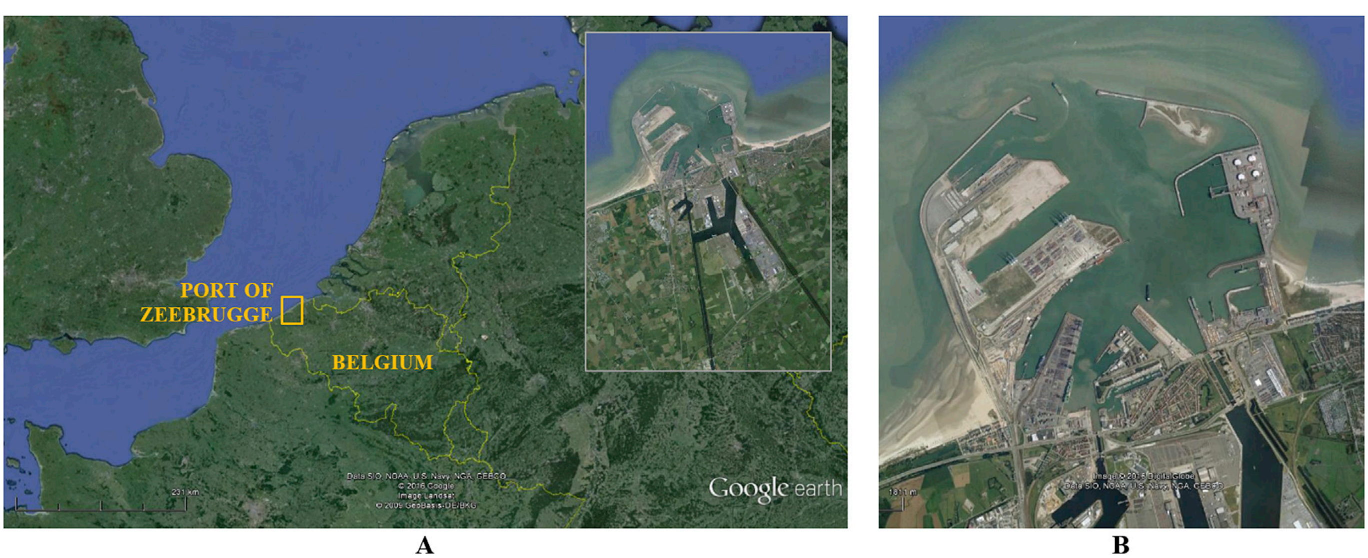

Fig. 1. Location of the case study site. A: Belgian coast and harbour of Zeebrugge (inset); B: Outer harbour of Zeebrugge (source: ©Google earth).