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Implementation and validation of a multi-domain coastal hazard forecasting system in an open bay

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A R T I C L E I N F O

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A B S T R A C T

European coasts are increasingly threatened by hazards related to low-probability and high-impact hydro-meteorological events. Uncertainties in hazard prediction and capabilities to cope with their impact lie in both future storm pattern and increasing coastal development. Therefore, adaptation to future conditions requires a re-evaluation of coastal Disaster Risk Reduction (DRR) strategies and introduction of a more efficient mix of prevention, mitigation and preparedness measures. The latter presumes that development of tools, which can manage the complex process of merging data and models and generate products on the current and expected hydro-and morpho-dynamic states of the coasts, such as forecasting system of flooding and erosion hazards at vulnerable coastal locations (hotspots), is of vital importance. Output of such system can be of an utmost value for coastal stakeholders and the entire coastal community. In response to these challenges, Delft-FEWS (Flood Early Warning System) provides a state-of-the-art framework for implementation of such system with vast capabilities to trigger the early warning process. In addition, this framework is highly customizable to the specific requirements of any individual coastal hotspot. Since its release, many Delft-FEWS based forecasting system related to inland flooding have been developed.

In this paper, a set-up of Delft-FEWS based forecasting system for Varna Bay (Bulgaria) and a coastal hotspot, which includes a sandy beach and port infrastructure, is presented. The system output generated in hindcast mode is validated with available observations of surge levels, wave and morphodynamic parameters for a sequence of three short-duration and relatively weak storm events occurred during February 4–12, 2015. Generally, while a longer term system operation/validation is needed for the model skills to be affirmed, the results obtained indicate a reliable prediction of coastal hazards, thus giving a sound basis for estimation of hazard impact.

1. Introduction

Storms are one of the most significant hydro-meteorological phenomena producing coastal flooding and endangering human life and occupation on European coasts. Moreover, storms cause diverse morphological changes some of which could have significant environmental and/or economic consequences. Therefore, model predictions on current and expected near-shore and coastal hydro- and morphodynamic states related (but not exclusively) to storm occurrence can be used to support decision making on Disaster Risk Reduction (DRR) response. Using this information, the impact of coastal hazards, such as coastal flooding and beach erosion, can be predicted and eventually mitigated.

One of the tools, which can manage the complex process of merging data and models and to generate products on current and expected hydro- and morpho-dynamic state of the coasts, is a coastal forecasting system (Bogaard et al., 2016). Such systems form a special class of environmental decision support systems as they operate in real time, rather than as a tool in support of strategic planning (Matthies et al., 2007). Output of such system can be valuable for coastal stakeholders and the entire coastal community with coastal stakeholders being all interested parties engaged in management and profitable utilization of the hotspot resources and infrastructure, while coastal community includes the local population related to the sea.

This paper aims to present the process of implementation and validation of a coastal forecasting system for a hotspot of national importance located in Varna Bay (Bulgaria), which is based on Delft-FEWS (Flood Early Warning System).

The foundation of Delft-FEWS is data-centric with a common data-model interface, through which all components interact. The main purpose of this framework is to provide a platform for building of an

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operational forecasting system that allows flexible integration of data and models (Werner et al., 2013). Initially developed for operational forecasting of river flow and potential inland flooding (Burnash and Singh, 1995; Werner et al., 2005), Delft-FEWS has evolved to cover marine and coastal hazards (De Kleermaeker et al., 2012). Nowadays, through activities within the RISC-KIT (*Resilience-Increasing Strategies for Coasts - toolKIT*) project, this platform is being further developed by extending its functionality to serve coastal early warning systems (Bogaard et al., in this issue).

Unlike other well-developed systems focused on forecasting of near-shore circulation, for instance (Stanev et al., 2011), or waves (Inghilesi et al., 2012) – the coastal FEWS concept goes beyond by translating near-shore (boundary) conditions to onshore coastal hazards, such as flooding, wave overtopping and erosion. This makes estimation of expected hazard extents and intensities in terms of, for instance, inundation depth or beach erosion possible.

Application of similar near-shore model systems has been demonstrated previously. For example, Verlaan et al. (2005) make use of the hydrodynamic model DCSM (Dutch Continental Shelf Model) in order to predict storm surge and tidal amplitude at the Dutch coast. Aimed at coastal monitoring along the Dutch coast, Baart et al. (2009) introduced a real time forecasting operational system in order to predict and hindcast morphological storm impacts. In line with this trend, Van Ormondt et al. (Van Ormondt et al., 2012) demonstrated the potential of the forecasting system CoSMoS (Coastal Storm Modelling System), a prototype version of the coastal FEWS, to predict dune and beach erosion during storms, as well as hazardous swimming conditions during calmer marine weather. Furthermore, Sembiring et al. (2015) reported another application of the generic CoSMoS system, which is not limited only to storm impact prediction but can be used to assess other coastal hazards, such as rip currents and flooding.

A near-real time coastal operational system was also established in the Black Sea. It provides nowcast and forecast of off-shore sea level and circulation (Kubryakov et al., 2012). Data originating from this system together with wave forecast, generated using operational meteorological data, were employed to test an early warning system prototype for a stretch of sandy Shkorpilovtsi beach in Bulgaria (Valchev et al., 2014). This event-based system predicted the storm impact on the beach using a set of indicators, which convert model results to coastal hazards, such as depth-velocity, flooding and erosion, and resulted in adequate warnings and series of actions to be undertaken by responsible authorities. However, this system could not be sustained due to lack of continuous operational forcing and boundary conditions data and, more importantly, lack of a suitable platform to guide and monitor the forecasting process – issues that are resolved in the current application.

As shown by Harley and Ciavola (2013), local coastal inundation risk can be managed by a combination of a forecasting system and suitable DRR measures such as artificial dune placement. Clearly, hazard evaluation is not the pinnacle which a coastal early warning system can reach. It can be complemented by additional modules, bridging hazard and impact assessment, and ultimately providing guidance for operation of possible response and preparedness measures.

Aiming at such sophisticated system, RISC-KIT made a progress towards impact-oriented forecasting by developing a Bayesian Decision Support System (DSS) (Jäger et al., 2017), which connects site specific geomorphic setting, hazard extent and intensities, and coastal vulnerability indicators, such as flood depth damage and erosion, in order to estimate socio-economic impact. Moreover, it can predict to what extent the impact can be reduced by implementation of various DRR measures. Similarly to all RISC-KIT case study sites, Bayesian DSS was also developed for Varna. However, discussion on this module is not considered herein. Some details can be found in (Cumiskey et al., in this issue).

This paper provides an overview of a coastal forecasting system implementation on four nested domains (Section 3). The study site settings are described in Section 2. Validation of the system through comparison of model output with field observations (surge, waves and onshore hazard modeling) together with visualization examples are presented in Section 4. Finally, in Section 5, an insight on obstacles, limitations and future challenges is presented.

2. Study site

The study site is part of Varna regional coastline (Bulgaria), which is located on the western Black Sea. The Black Sea is an elliptical semi-closed basin with weak tides (about 8 cm) with a complex orography located in south-eastern Europe. The western coastal region is relatively low in comparison to eastern and southern ones (Fig. 1A). The area of the Black Sea shelf is about 24% of the total basin area and its outer edge can be traced along the 100–150 m depth contour (Fig. 1B). The Black Sea can be considered a fairly busy sea comprising various economic activities such as ship traffic, fisheries, aquafarming, gas exploration and recreation.

Varna regional coastline is approximately 70 km-long and includes Varna Bay, which is an open bay stretching from cape St. George to the north to cape Galata to the south (Fig. 1C). Its northern arm is entirely protected by coastal defence structures – rocky revetments, groynes and jetties – that resulted in formation of several beaches. In the innermost part of Varna Bay there is a sandy spit – low elevation area, nowadays cut by two artificial navigable canals connecting Varna Bay to Varna Lake. It holds the largest transport and port agglomeration industrial complex in Bulgaria. Another important regional economic activity is tourism, which supports large seaside resorts, as well as small restaurants, beach bars, shops, sport and leisure facilities scattered along the coastline. Varna is the only coastal city in Bulgaria that marks a population growth (2.8%) (National Statistical Institute, 2011).

The selected hotspot (Fig. 2) – a highly vulnerable coastal sector according to Valchev et al. (2016) – includes Varna beach and the breakwater of Port of Varna (herein referred to as port wall). Varna beach is a 1.2 km-long exposed to ESE sand body of variable width – from 5 m in the northernmost to 110 m in the southernmost part. It is backed by a 10 to 18 m-high cliff and is bordered by a Y-head groyne to the north and by the port wall to the south. Beach slope varies between 0.09 and 0.18 and sediment grain size – between 0.28 and 0.81 mm. The port wall is a part of the port agglomeration industrial complex. It is a 1.18 km-long concrete structure with maximum height of 7.2 m. The port wall embankment consists of rocks and tetrapods.

Varna Bay has experienced extreme historical storms propagating in from the eastern half with the main sources of hazard being high storm surges, large waves and coastal erosion (Galabov et al., 2015; Trifonova et al., 2012; Valchev et al., 2012). These events caused damages to beaches, along with port and other coastal structures, touristic and private property (Andreeva et al., 2011; Stakev, 1980).

3. Coastal forecasting system set-up

The primary objective of the coastal forecasting system is to provide predictions, with sufficient lead time, of coastal hazards resulting from short-term hydro-meteorological conditions. These hazard predictions can be then used for impact assessment and eventually as a basis for making decision to take warning and response actions. This is ensured by the ability of the Delft-FEWS platform to integrate real-time data from various observation and forecasting networks, to generate predictions and to disseminate results through appropriate products to the warning process (Werner et al., 2013).

3.1. Structure and models

The system structure is designed to guarantee a smooth forecasting process that is a sequence of steps starting with data import, continuing with a number of data processing and modelling steps, and resulting in generation of products to be disseminated through user interface (Werner et al., 2013). In the current application, hydrodynamic and