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Predicting coastal hazards for sandy coasts with a Bayesian Network

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ABSTRACT

Low frequency, high impact storm events can have large impacts on sandy coasts. The physical processes governing these impacts are complex because of the feedback between the hydrodynamics of surges and waves, sediment transport and morphological change. Predicting these coastal changes using a numerical model requires a large amount of computational time, which in the case of an operational prediction for the purpose of Early Warning is not available. For this reason morphodynamic predictions are not commonly included in Early Warning Systems (EWSs). However, omitting these physical processes in an EWS may lead to potential under or over estimation of the impact of a storm event.

To solve this problem, a method has been developed to construct a probabilistic Bayesian Network (BN). This BN connects three elements: offshore hydraulic boundary conditions, characteristics of the coastal zone, and onshore hazards, such as erosion and overwash depths and velocities. The hydraulic boundary conditions are derived at a water depth of approximately 20 m from a statistical analysis of observed data using copulas, and site characteristics are obtained from measurements. This BN is trained using output data from many pre-computed process-based model simulations, which connect the three elements. Once trained, the response of the BN is instantaneous and can be used as a surrogate for a process-based model in an EWS in which the BN can be updated with an observation of the hydraulic boundary conditions to give a prediction for onshore hazards.

The method was applied to Praia de Faro, Portugal, a low-lying urbanised barrier island, which is subject to frequent flooding. Using a copula-based statistical analysis, which preserves the natural variability of the observations, a synthetic dataset containing 100 events was created, based on 20 years of observations, but extended to return periods of significant wave height of up to 50 years. These events were transformed from offshore to onshore using a 2D XBeach (Roelvink et al., 2009) model. Three BN configurations were constructed, of which the best performing one was able to predict onshore hazards as computed by the model with an accuracy ranging from 81% to 88% and predict events with no significant onshore hazards with an accuracy ranging from 90% to 95%. Two examples are presented on the use of a BN in operational predictions or as an analysis tool.

The added value of this method is that it can be applied to many coastal sites: (1) limited observations of offshore hydrodynamic parameters can be extended using the copula method which retains the original observations' natural variability, (2) the transformation from offshore observations to onshore hazards can be computed with any preferred coastal model and (3) a BN can be adjusted to fit any relevant connections between offshore hydraulic boundary conditions and onshore hazards. Furthermore, a BN can be continuously updated with new information and expanded to include different morphological conditions or risk reduction measures. As such, it is a promising extension of existing EWSs and as a planning tool for coastal managers.

1. Introduction

Over the past decades a number of large storm events have demonstrated the vulnerability of the coastal zone in Europe, such as to the North Sea Flood of 1953 in the Netherlands, Belgium and the United Kingdom (Gerritsen, 2005), Xynthia (2010) affecting the entire coast of south-western Europe (Bertin et al., 2012) and Hercules (2014) causing severe coastal erosion and flooding in parts of France and the United Kingdom (Masselink et al., 2015a) among many others. Larger and more extreme events such as the hurricanes in the USA, e.g. Katrina in 2005 (Knabb et al., 2006) and Sandy in 2012 (Blake et al., 2013), and Typhoons in Asia, e.g. Haiyan in 2013 and Nargis in 2008, have also shown the devastating effects of these low-frequency, high impact flood events.

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Sandy coasts are especially vulnerable as they exhibit large responses to these low-frequency high impact events, such as extensive beach and dune erosion (Castelle et al., 2015; Masselink et al., 2015b), and even breaching (Roelvink et al., 2009; McCall et al., 2010). Buildings and infrastructure built on these sandy coasts are not only vulnerable to flooding but also to damage caused by overwash and coastal erosion (Smallegan et al., 2015). Furthermore, extreme overwash and breaching can alter the barrier and lagoon morphology and possibly affect the water level inside the lagoon, changing the back barrier flooding hazard.

Coastal hazard prediction has long been the focus of the scientific and coastal management community. Early approaches were mainly focused on the classification of offshore hazard based on wave power (Dolan and Davis, 1992) or associated coastal response (like erosion) to offshore forcing (Miller and Livermont, 2008; Mungar and Kraus, 2010). The most commonly-used approaches to derive coastal hazards use simple relations (Kriebel and Dean, 1993; Larson et al., 2004; Mendoza and Jiménez, 2006; Stockdon et al., 2007). Using hindcasted or operational predictions of wave and surge levels with or without flood propagation, coastal impacts such as flooding over an invariant topography are computed using the "bathtub" or flooded valley approach (Leatherman, 1990; Carrasco et al., 2012). Overwash is routinely computed using empirical equations (e.g. (Rodrigues et al., 2012)), and beach erosion using static models (e.g. (Ferreira et al., 2006)). Due to the complexity of the storm processes Stockton et al. (2007) classified storm impact based for the different regimes proposed by (Sallenger, 2000). The above consider each hazard separately and do not include the morphodynamic response of a coast to high impact events and usually do not include feedback mechanisms between waves, currents, sediment transport and morphological change. For sandy shores with beaches and dunes the coastal morphological response is non-negligible and influences the pathway of a coastal hazard to the hinterland, changing for instance the flood duration, the extent and the depth fields (McCall et al., 2010; Cañizares and Irish, 2008). Current models can therefore under or over predict the hazard intensities and impact of coastal hazards on sandy coasts, both of which are detrimental for planning or evacuation purposes.

Morphodynamic process-based models such as XBeach (Roelvink et al., 2009) are capable of simultaneously computing wind- and wave-induced water levels and velocities as well as the associated morphological response. However, these models are complex, which comes at the expense of increased computational cost. This poses a problem for the use of such models in an Early Warning System (EWS), where the computational window is limited to the short period between successive, updated meteorological forecasts. Early attempts to incorporate morphodynamic models in EWS (Plomaritis et al., 2012; Vousdoukas et al., 2012a) resulted in simplification of the morphology to several 1D profiles in order to increase the models operability.

To solve this problem, a solution is proposed in which a probabilistic model based on a Bayesian Network (BN) is utilized as a surrogate for a process-based model. A BN is in essence a probabilistic graphical model, which consists of random variables and conditional dependencies between said variables. The random variables are the hydraulic boundary conditions (defined at the 20 m depth contour), such as the surge and wave parameters, and the onshore hazard intensities, such as erosion, overwash depths and flow velocities. The conditional dependencies between the random variables can be determined by training the BN using output data from many pre-computed process-based model simulations, as well as from observations. Once trained, the response of the BN is instantaneous. It can be included in an operational EWS in which the BN can be conditioned with predicted waves and water levels from offshore hydrodynamic models to produce a prediction for onshore coastal impacts.

BNs have been proven useful in a number of coastal applications. Hapke & Plant (2010) applied them to predict cliff erosion by connecting the forcing variables (e.g. wave conditions) and initial conditions (e.g. cliff geometry). Dune erosion volumes due to storm impact, as predicted by an empirical model, have also been reproduced by a BN (Den Heijer et al., 2012). A BN has been used to predict coastal vulnerability to sea level rise (Gutierrez et al., 2011), and to assess the interactions between barrier island geomorphic variables (Gutierrez et al., 2015). Van Verseveld et al. (2015) applied it 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. In this paper, we will build on this previous work and apply the BN to relate offshore hydraulic boundary conditions to onshore hazards through a transformation using process-based model simulations.

The key point of this paper is the development of a method in which a BN is a surrogate for a process-based model within an EWS. The main focus of the paper is on the development of a generic method with an application on a low-lying barrier coast which serves as an example. In this paper, we will focus on the method and application, and provide references to background literature on the individual elements.

In Section 2, a method is developed to construct a BN, which is a surrogate for a complex process-based model and can be implemented in an EWS for urbanised sandy coasts. The method is applied in the case study site of Praia de Faro (Algarve, Portugal) in Section 3. The discussion is in Section 4 and a summary and conclusions are presented in Section 5.

2. Methods

A probabilistic model, a BN, will be constructed which can be used as a surrogate for a process-based coastal morphodynamic model in an EWS. A BN consists of nodes and arcs, in which the nodes represent the variables of interest and the arcs indicate the conditional dependencies between them (Pearl and Russel, 1988). When the nodes and arcs are set up the network can be trained with a dataset, which may consist of observations or of synthetic numerical model results. In the present application the BN will be trained with the results of a process-based numerical model which is able to transform a range of offshore hydraulic boundary conditions (water levels, wave heights, wave periods, etc.) in deeper water, typically at 20 m depth, to onshore hydrodynamic (water depths and currents) and morphological (erosion) hazards on the coast. Hydraulic boundary conditions will be derived from a statistical analysis of observational data. The combination of the hydraulic boundary conditions and onshore hazards simulated in the process-based model forms the dataset that trains the BN. Once the BN is trained it can be conditioned with an observation, or prediction, of the hydraulic boundary conditions to give a prediction of onshore hazards.

The method involves five steps: (1) a dataset from which conditions with large return periods can be derived is synthesised if long-term observations are not available (which is usually the case), (2) the time variation of the offshore hydrodynamic parameters during an event is schematised, (3) a process-based model is constructed to transform the offshore hydraulic boundary conditions to onshore hazards (4) a BN is set up that is sufficiently complex (in terms of nodes and arcs) to represent the relations between variables, yet as simple as possible to minimise the required amount of training data and (5) metrics are determined to assess the predictive value of the BN.

2.1. Synthesis of extreme events

The first step is to obtain a large enough dataset from which extreme conditions can be derived to train the BN. If long-term observations are not available, this dataset needs to be synthesised, for which a method using copulas (Sklar, 1959) is applied. Copulas are mathematical tools that can be used to construct multivariate distributions. An example are storm events which can be characterised by a set of random variables such as the significant wave height, surge level, storm duration and peak wave period. The interrelations between these variables may be characterised by a multivariate probability distribution. Classical parametric families of multivariate distributions, e.g. Gaussian,