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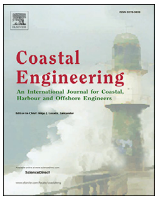

A Bayesian network approach for coastal risk analysis and decision making

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ABSTRACT

Emergency management and long-term planning in coastal areas depend on detailed assessments (meter scale) of flood and erosion risks. Typically, models of the risk chain are fragmented into smaller parts, because the physical processes involved are very complex and consequences can be diverse. We developed a Bayesian network (BN) approach to integrate the separate models. An important contribution is the learning algorithm for the BN. As input data, we used hindcast and synthetic extreme event scenarios, information on land use and vulnerability relationships (e.g., depth-damage curves). As part of the RISC-KIT (Resilience-Increasing Strategies for Coasts toolKIT) project, we successfully tested the approach and algorithm in a range of morphological settings. We also showed that it is possible to include hazards from different origins, such as marine and riverine sources. In this article, we describe the application to the town of Wells-next-the-Sea, Norfolk, UK, which is vulnerable to storm surges. For any storm input scenario, the BN estimated the percentage of affected receptors in different zones of the site by predicting their hazards and damages. As receptor types, we considered people, residential and commercial properties, and a saltmarsh ecosystem. Additionally, the BN displays the outcome of different disaster risk reduction (DRR) measures. Because the model integrates the entire risk chain with DRR measures and predicts in real-time, it is useful for decision support in risk management of coastal areas.

1. Introduction

About 10% of the world's population lives in low-lying coastal areas, where they are vulnerable to extreme events generated by the combined impact of waves, surges and tides (McGranahan et al., 2007). For example, if the sea surface elevation is higher than a coastal defense, water overtops (Hubbard and Dodd, 2002) or overflows (Reeve et al., 2008) the structure and floods the hinterland. Moreover, engineered flood defenses may fail catastrophically under extreme loading conditions (Vrijling, 2001; Sills et al., 2008). Similarly, beach and dune erosion at sandy coasts can threaten structures close to the shoreline or result in breaches and inundation (Vellinga, 1982; Visser, 1998). As a consequence, coastal communities may suffer from material damages, economic, political and social disruption, health issues, or damaged ecosystems (Jonkman et al., 2008a).

Under extreme circumstances, coastal storms can lead to societal disasters. For example, around 1100 lives were lost when Hurricane Katrina made landfall in New Orleans in 2005 (Jonkman et al., 2009a). More recently, 47 people died in La Faute-sur-Mer, France, during storm Xynthia in 2010 (Bertin et al., 2012). These events emphasize a continuing need for effective coastal risk management; this is all the more important as risks are projected to increase globally, due to growing populations and assets, accelerated sea level rise and potential increases in storminess (both tropical and extra-tropical) (Hallegatte et al., 2013).

Coastal risk management essentially includes two types of activities: taking prompt actions in the face of an impending storm and long-term planning. Accordingly, we distinguish between a *hot phase* and a *cold phase*. In the hot phase, emergency managers depend on real-time and reliable predictions of the expected conditions in the coastal zone, as they attempt to select mitigation measures and allocate limited resources minimizing the total sum of negative impacts. In the cold phase, multiple actors, including politicians, local stakeholders and scientists, cooperate to determine sensible strategies for reducing risks in an uncertain future (Ernsteins, 2010). To evaluate these strategies against historical and conceivable future storms, they turn to impact assessments of the various scenarios.

Cutting across numerous disciplines, including oceanography, coastal science and engineering, statistics, economics, and social and political

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science, coastal risk assessment is highly challenging. Each field has complex models which target individual elements of the risk process. For example, multivariate probability models estimate the return periods of extreme storms (De Michele et al., 2007; Wahl et al., 2016), while numerical models, based on, for instance, hydro- and morphodynamic processes, determine the respective natural responses of the coast and extent of flooding (Warren and Bach, 1992; Hervouet, 2000; Bates and De Roo, 2000; Roelvink et al., 2009). Finally, behavioral or statistical models estimate the diverse and complex consequences onshore (Ahern et al., 2005; Hajat et al., 2005; Jonkman et al., 2009a; Merz et al., 2010). However, risk management requires a framework that integrates the individual elements of the risk process (Brouwer and Van Ek, 2004).

Two primary issues arise when attempting to incorporate offshore sea conditions with their expected onshore hazards and impacts into a single model for operational use. Numerical models, being computationally expensive, often have a long run time, while instant assessments are needed for any conceivable hazard scenario during both the hot and cold management phases. On the other hand, the spatial and temporal scales of numerical and impact models differ from one another and need to be integrated. Whereas numerical models have grids whose sizes depend on the physical properties of the area under consideration, impact models usually operate on the level of individual receptors.

In the Netherlands, Jonkman et al. (2008a) assessed the flood hazard and corresponding damages to the built environment, loss of life, as well as indirect economic impacts (e.g., the interruption of production flows) for one hypothetical extreme event. The fundamental element of this approach is a spatial database through which they connect output and input of the individual models according to a common spatial attribute. While addressing the challenges of different scales, the approach was limited to a single storm scenario. In principle, other storms could be assessed similarly, but the computational time is determined by the underlying numerical models. For this reason, the approach may not be suitable to predict flood hazards and damages for an impending storm or to compare multiple hypothetical storm scenarios during round-table discussions of stakeholders.

In contrast, Poelhekke et al. (2016) integrated a wide range of simulated storm scenarios in a discrete Bayesian network (BN) and assessed related onshore hazards in Praia de Faro, Portugal. A BN is a graphical model that describes system relations in probabilistic terms and can give instantaneous predictions. Nevertheless, Poelhekke's approach did not estimate impacts nor does it provide insight into the effectiveness of risk reduction measures. As far as we know, no model has been proposed which renders instant assessments for various possible storm scenarios and captures the entire risk chain from sea conditions to onshore impacts.

In this article, we design a decision support system (DSS) for the hot and cold phases of coastal risk management as a BN. We build on the widely recognized *source-pathway-receptor* (SPR) concept and attempt to extend and generalize the work of Poelhekke et al. (2016). The DSS is part of a suite of tools, developed in the RISC-KIT project, whose purpose is to help effective disaster risk reduction (DRR) management at coasts (van Dongeren et al., 2017). For different extreme event scenarios, the BN predicts percentages of affected receptors in terms of the hazards experienced and their impacts in real-time. Moreover, the BN can evaluate the effects of potential DRR measures. Although our focus is on marine storms, which are the primary threat to coastline stability, the approach is broader. It is also possible to include, or even solely concentrate on, other types of natural disasters, such as extreme river discharges or exceptional rainfall events in this model.

The remainder of the paper is organized as follows. In Section 2, we introduce the methodological background. We explain the SPR-concept and provide the basic theory of discrete BNs. In Section 3, we describe the design of the DSS, followed by examples from the case study site of Wells-next-the-Sea, Norfolk, UK, in Section 4. Finally, in Section 5, we discuss limitations and potential of the approach and, in Section 6, we present our conclusions.

2. Methodological background

In this section we provide an overview of models for the different elements in the risk chain, following the logic of the source-pathway-receptor concept, as well as an approach to quantitatively assess the effect of DRR measures. After that we describe the method we use to integrate the various models and DRR measures: BNs.

2.1. The source-pathway-receptor concept

The *source-pathway-receptor* (SPR) concept is a high-level framework to evaluate risks. It was first used to describe the possible movements of a pollutant from its source to a receptor (Holdgate, 1980) and is now well established in coastal risk management (Sayers et al., 2002; Evans et al., 2004; Narayan et al., 2012; Burzel et al., 2010).

In its basic form, the framework characterizes a causal chain of processes and events in terms of sources, pathways and receptors (Fig. 1). When considering coastal storms, the chain reaches from offshore to onshore. The *source* is the offshore marine environment. Typical source variables, or *boundary conditions*, are peak water level, maximum wave height and peak period, and storm duration. The storm threat can affect onshore areas through *pathways*. They are the interaction of water levels and waves with coastal landforms and ecosystems, coastal infrastructure and low-lying coastal hinterlands. Finally, *receptors* are the entities at risk, such as people, built environments or ecosystems.

Sometimes, the framework explicitly includes *consequences* (C) as a fourth term. Any receptor can experience them, if affected by a *hazard.* Gouldby and Samuels (2005) have defined a hazard as the triple: source, pathway and receptor. However, we consider a hazard to be a local condition directly affecting the receptors. Examples are flood depth, flow velocity and erosion, which can, for instance, cause structural damage or injuries.

Coastal risk assessments often follow this concept. The general idea is to generate a set of representative extreme event scenarios, model the pathways, and estimate the resultant impact (e.g., Oumeraci et al., 2015). More specifically, detailed and specific models are applied to various individual processes in the SPRC chain and then linked together. However, to the best of our knowledge, a single model that captures the entire chain does not exist yet.

2.1.1. Source models

A set of scenarios that are representative for the storm climate at a given site can be derived from a statistical analysis. Often, storms are characterized by the values of hydraulic variables in deep water at the peak of the storm along with its duration. In the past decade, copula-based models have become increasingly popular to estimate dependencies between (some) such variables (e.g., De Michele et al., 2007; Corbella and Stretch, 2012; Salvadori et al., 2014; Wahl et al., 2016). A copula is a specific type of probability distribution that characterizes the dependence structure between random variables irrespective of their marginal behavior. The temporal evolution of the variables, which is typically required as input for pathway models, is often idealized as a so-called *equivalent triangle* (Boccotti, 2000). Nonetheless, a couple of studies model times series explicitly (Wahl et al., 2012; Jäger and Morales Nápoles, 2017).

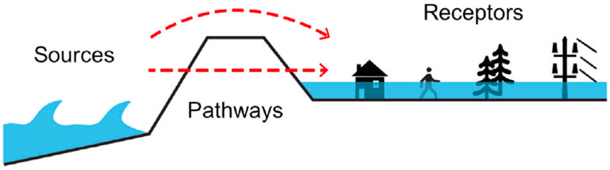

Fig. 1. Illustration of the source-pathway-receptor (SPR) concept for coastal storms.