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Uncertainty and sensitivity of flood risk calculations for a dike ring in the south of the Netherlands

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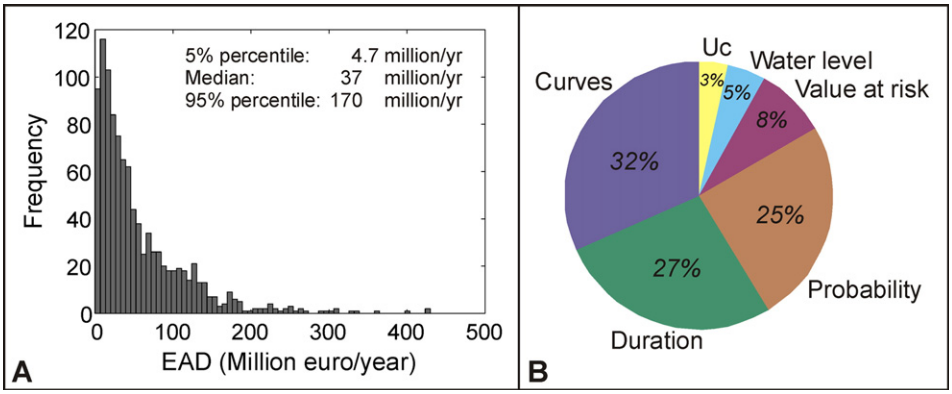
HIGHLIGHTS

- We model flood risk (expected annual damage) for a dike ring along the river Meuse.
- Uncertainty and sensitivity of flood risk are assessed using coupled models.
- Uncertainty is substantial: 8 times lower, to 4.5 times higher than median (90%).
- Mainly probability, duration and damage curve are responsible for uncertainty.
- Uncertainty and sensitivity depend considerably on local characteristics.

GRAPHICAL ABSTRACT



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ABSTRACT

A central tool in risk management is the exceedance-probability loss (EPL) curve, which denotes the probabilities of damages being exceeded or equalled. These curves are used for a number of purposes, including the calculation of the expected annual damage (EAD), a common indicator for risk. The model calculations that are used to create such a curve contain uncertainties that accumulate in the end result. As a result, EPL curves and EAD calculations are also surrounded by uncertainties. Knowledge of the magnitude and source of these uncertainties helps to improve assessments and leads to better informed decisions. This study, therefore, performs uncertainty and sensitivity analyses for a dike-ring area in the Netherlands, on the south bank of the river Meuse. In this study, a Monte Carlo framework is used that combines hydraulic boundary conditions, a breach growth model, an inundation model, and a damage model. It encompasses the modelling of thirteen potential breach locations and uncertainties related to probability, duration of the flood wave, height of the flood wave, erodibility of the embankment, damage curves, and the value of assets at risk. The assessment includes uncertainty and sensitivity of risk estimates for each individual location, as well as the dike-ring area as a whole. The results show that for the dike ring in question, EAD estimates exhibit a 90% percentile range from about 8 times lower than the median, up to 4.5 times higher than the median. This level of uncertainty can mainly be attributed to uncertainty in depth–damage curves, uncertainty in the probability of a flood event and the duration of the flood wave. There are considerable differences between breach locations, both in the magnitude of the uncertainty, and in its source. This indicates that local characteristics have a considerable impact on uncertainty and sensitivity of flood damage and risk calculations.

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1. Introduction

Flood risk assessments aim to estimate current flood risk or projected changes in flood risk due to certain (future) developments (e.g. Bouwer et al., 2010; Te Linde et al., 2011; Beckers et al., 2013) or measures (e.g. De Kok and Grossmann, 2010; Te Linde et al., 2010; De Moel et al., in press; Koks et al., in press). Flood risk is in this respect generally defined as a combination of the probability of a flood event (or return period) and its consequences (Kron, 2002; Samuels and Gouldby, 2005). The consequences of a flood are commonly quantified in monetary terms (i.e. flood damage). In many countries methods have been developed to estimate flood damages, such as HAZUS in the USA (Scawthorn et al., 2006), the multi-coloured manual in the UK (Penning-Rowsell et al., 2010), FLEMO in Germany (Thieken et al., 2008), HIS-SSM in the Netherlands (Kok et al., 2005), and many more studies from all over the world (e.g. Dutta et al., 2003; URS, 2006; Luino et al., 2009; Huttenlau et al., 2010; Middelmann-Fernandes, 2010). Calculations of flood damage for different return periods can be combined in a so-called exceedance probability-loss (EPL) curve, which provides estimated flood damage corresponding to different return periods. Such an EPL curve can be used to calculate the expected annual damage (EAD) of flooding in a certain region. This EAD is one of the principal risk indicators used and is given by the area under the EPL curve (or integral) (Meyer et al., 2009; Ward et al., 2011).

These EPL curves and corresponding estimates of EAD play an important role in flood management. For instance, decision makers that plan to invest public resources in flood protection measures can use EAD estimates to assess the benefits of such investments (e.g. Pearce and Smale, 2005; Hallegatte, 2006). Moreover, EPL curves and EAD estimates are of particular importance to insurance companies, who use them, for example, to calculate premiums (Freeman and Kunreuther, 2003). However, estimates on both the magnitude of a flood event and estimates of its corresponding consequences are inherently uncertain (Apel et al., 2004; Van Gelder, 2008; Merz and Thieken, 2009; De Moel and Aerts, 2011). There are several studies that have addressed uncertainties in flood damage and risk assessments. Most of these studies focused on uncertainties in single components of a damage or risk assessment, such as the water depths in floodplains (Hall et al., 2005; Noack and Yoruk, 2008) or the damage calculation (Merz et al., 2004; Egorova et al., 2008). However, some recent studies also addressed uncertainty in multiple components (e.g. Apel et al., 2008; Merz and Thieken, 2009; Freni et al., 2009; De Moel et al., 2012; Saint-Geours et al., 2013). Very few, however, have addressed uncertainties in the EPL curves that underlie flood risk estimates (Aerts et al., 2013).

This study aims to assess uncertainties in flood damage estimates and flood probabilities in order to construct confidence intervals around an EPL curve. Uncertainty analyses as well as sensitivity analyses will be performed in order to identify the input parameters that most strongly influence risk estimates. This will be done using a Monte Carlo framework that combines hydraulic boundary conditions, a breach growth model, an inundation model, and a damage model. The methodological framework is almost the same as described in De Moel et al. (2012), who investigated uncertainties in flood damage assessments due to coastal flooding in the west of the Netherlands. However, in this study fluvial flooding is investigated rather than storm surges, resulting in the inclusion of different parameters. Moreover, some parameters that were previously found to be of little influence have been excluded in this research (e.g. the initial width of the breach, time of vertical erosion). Furthermore, this study expands the framework by including the probability of a flood event (and uncertainty therein), resulting in the analysis of uncertainty and sensitivity of flood risk estimates as opposed to flood damage estimates. The case-study area for this analysis is a large dike-ring area in the south of the Netherlands, along the banks of the river Meuse.

2. Case study area

This study will discuss potential flood damage and risk calculations for a case-study area in the south of the Netherlands, on the south bank of the river Meuse. The case-study area consists of a dike ring (number 36) known as *Land van Heusden/de Maaskant*. Dike rings are geographical units surrounded by flood defences or high grounds. In total, the Netherlands has almost a hundred dike rings, with differentiated safety norms ranging from 1/250 per year to 1/10,000 per year (Ministerie van V&W, 2007). Dike ring 36 has a design norm of 1/1250 per year and houses around 400,000 inhabitants. The area covers approximately 740 km^2 and is mainly used for agriculture. There are, however, also two main cities (Den Bosch and Oss) and various important highways and railroads. Dike ring 36 has been the subject of a number of other studies, including VNK (2006), who identified thirteen possible breach locations and estimated inundation depths and flood damage for these thirteen breach scenarios. Bouwer et al. (2009) used these thirteen breach locations and developed a series of 42 inundation scenarios with corresponding flood damages in order to construct EPL curves for the current situation and for several future projections of climate and land-use change (Bouwer et al., 2010). In this study, we will also look at the thirteen breach locations identified by VNK (2006) and used by Bouwer et al. (2009) (Fig. 1).

3. Methodology

In this study we build on the model framework as developed by De Moel et al. (2012). In this approach a breach growth model (see Section 3.1.2), inundation model (see Section 3.1.3) and damage model (see Section 3.1.4) are dynamically coupled and integrated in a Monte Carlo framework in order to estimate the uncertainty in the resulting damage and risk estimates (Fig. 2). For this study, this framework was extended by risk calculations, which combines the probability with the estimated damage to arrive at annual damage (i.e. risk). This is done for individual simulations at a breach location (EAED) and, as well as the aggregate of all 13 breach locations to generate the annual damage for the dike ring as a whole (EAD) (see Section 3.3).

To assess potential flood damage and risk, first the flood wave is determined, which denotes the water level on the river over time. In order to arrive at this flood wave, the standard flood wave used by Dutch engineers is adjusted to represent a specific return period for the simulation, including uncertainty in this return period. Moreover, the standard flood wave is adjusted by considering uncertainty in the duration and the highest water level of the flood wave (Fig. 2). The flood wave is then fed into a coupled breach growth and inundation model. This is where uncertainty in the material of the embankment is considered. The resulting inundation map is subsequently used by the damage model to calculate the flood damage corresponding to the simulation, in which uncertainty in the depth–damage curves and the values at risk are considered (Fig. 2).

For each breach location, 1024 model simulations were performed with six dynamic input parameters for which uncertainty was propagated through the modelling chain (see Section 3.2). By means of the method of Sobol (2001), 1024 quasi-random, unique combinations of the dynamic input parameters were generated using the Simlab toolbox for Matlab developed by the EU Joint Research Centre (Simlab, 2011). The total range of damage estimates illustrates the uncertainty of the damage calculation and the method of Sobol' was used to generate total sensitivity indexes, showing the relative contribution of each dynamic input parameter to the total variation. The following three subsections will elaborate first on the data and models used (Section 3.1), describe the uncertainty of the six dynamic input parameters (Section 3.2) and explain the risk indicators used in this study (Section 3.3).