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Impacts of rainfall variability and expected rainfall changes on cost-effective adaptation of water systems to climate change

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ABSTRACT

Stormwater drainage and other water systems are vulnerable to changes in rainfall and runoff and need to be adapted to climate change. This paper studies impacts of rainfall variability and changing return periods of rainfall extremes on cost-effective adaptation of water systems to climate change given a predefined system performance target, for example a flood risk standard. Rainfall variability causes system performance estimates to be volatile. These estimates may be used to recurrently evaluate system performance. This paper presents a model for this setting, and develops a solution method to identify cost-effective investments in stormwater drainage adaptations. Runoff and water levels are simulated with rainfall from stationary rainfall distributions, and time series of annual rainfall maxima are simulated for a climate scenario. Cost-effective investment strategies are determined by dynamic programming. The method is applied to study the choice of volume for a storage basin in a Dutch polder. We find that 'white noise', i.e. trend-free variability of rainfall, might cause earlier re-investment than expected under projected changes in rainfall. The risk of early re-investment may be reduced by increasing initial investment. This can be cost-effective if the investment involves fixed costs. Increasing initial investments, therefore, not only increases water system robustness to structural changes in rainfall, but could also offer insurance against additional costs that would occur if system performance is underestimated and re-investment becomes inevitable.

1. Introduction

There is growing evidence that climate change will lead to an increase of the intensity and frequency of heavy rainfall, the number and duration of droughts, and increasing peak river flows (Ekström et al., 2005; Frei et al., 2006; IPCC, 2007; Kirono et al., 2011; Lenderink et al., 2007; May 2008; Vrochidou et al., 2013). Water systems, including stormwater drainage, flood defence and water supply systems, are vulnerable to changes in rainfall and runoff and need to be adapted (Hoes and Schuurmans, 2006; Medellín-Azuara et al., 2008; Nie et al., 2009; te Linde et al., 2011). This paper studies impacts of rainfall variability and expected changes in the return periods of rainfall extremes on cost-effective adaptation of water systems to climate change given a predefined system performance target. System performance targets for water systems describe the minimum system performance that is required by law or institutional arrangements. Examples are flood risk standards for dike rings, flood risk standards for surface and urban drainage systems, and water quality limits for receiving waters (EC 2000; NBW, 2008; Kind, 2014).

Climate change impacts are uncertain, and technical lifetimes of infrastructure, such as sewers, open channels and dikes, are typically long (e.g. 100 years) and usually involve fixed costs (Arnbjerg-Nielsen, 2012; Read, 1997). An optimal mixture of initial climate change adaptation measures therefore accounts for the cost structure of available options (de Bruin and Ansink, 2011). Moreover, it has been suggested to compare the expected decrease in performance during a portion of the expected lifetime of the infrastructure with a predefined performance target (Mailhot and Duchesne, 2010). However, best estimates of extreme weather distributions, needed to evaluate infrastructure performance over time, are generally not reliable. This is due to the number of extreme value observations, weather variability, and uncertainty about the shift of extreme value distributions due to climate change

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(Huard et al., 2010; Rosenberg et al., 2010). Moreover, one or few new observations may change beliefs about the distribution parameters or distribution type, and hence about the return period of extreme events (e.g. Coles and Pericchi, 2003). Hitherto, the stormwater and flood risk management literature has paid surprisingly little attention to the likelihood of investment responses induced by new hydro-meteorological observations, and to the implications for initial investment decisions (e.g. Fletcher et al., 2013).

This paper analyses optimal investment levels in water system adaptations to keep water system performance in line with a system performance target under climate change. Effects of rainfall variability and projected structural changes in rainfall on cost-effective investment levels are studied. To this end, the optimisation problem is described mathematically. In addition, a solution method is developed and applied to identify cost-effective investment strategies for stormwater drainage system adaptations.

Fig. 1 summarises inputs and processes required for design decisions about elements of water systems. It includes: (i) hydro-meteorological observations from the case study area, for example weather, or peak flows observations, (ii) information about cost-structures and technical lifetimes, (iii) expected changes in extreme-value distributions, (iv) failure probabilities of the system before and after investment, (v) a system performance target, or other design rules, and (vi) an analysis of system failure probabilities over time based on simulated realisations of extremes. In the sequel, rainfall is used as observational input, failure probability is defined by flood probability, and a flood risk standard is applied to study cost-effective investment in stormwater infrastructure.

2. Rainfall variability

Traditionally, the design of stormwater infrastructure has been derived from so-called design storms. A critical design storm (CDS) specifies rainfall depth, i.e. rainfall quantity, for an assigned probability of occurrence and duration (e.g. De Michele 1998). Before simulation models were available, water system elements have often been designed separately with design storms, rather than by analysing the reliability of the system as a whole under a large number of rainfall events. System reliability is equal to one minus the joint failure probability of the system elements. For small water systems, system reliability ($\tilde{R}_t$) at moment t can be approximated by Eq. (1) if all individual system elements are designed for the same CDS. In Eq. (1), r_t is the average return period of the chosen design storm at moment t. Clearly, this is a rough approximation, for which an appropriate design storm duration, and representative synthetic rainfall events have to be selected (cf. Levy and McCuen, 1999; Mays, 2011).

$$\tilde{R}_t = \left(1 - \frac{1}{r_t}\right) \tag{1}$$

The CDS has to be chosen such that its average return period (r_t) in the future remains large enough to meet the reliability target under climate change. Analogue to the work of Mailhot and Duchesne (2010), the return period of the CDS could be chosen such that projected system reliability under a rainfall scenario intersects with the system reliability standard at the end of the compliance period. This is displayed in Fig. 2, where the compliance period is assumed to end by the year 2050.

Rainfall variability, however, causes reliability estimates to be volatile. To illustrate this, a moving window analysis was applied where the last 50 years of observations were used to estimate the return period of the original CDS (cf. De Michele et al., 1998). Future rainfall was simulated by random draws from the shifted (24-h) annual maximum rainfall distribution over time. Fig. 2 shows three main differences between projected reliability and reliability estimates. Firstly, projected reliability decreases monotonically, but reliability estimates do not due to rainfall variability. Secondly, median reliability estimates are larger than projected reliability. Thirdly, the lower bound of the 95%-confidence interval intersects with the reliability standard well before the intersection of the projected reliability with the standard.

Re-investment in the system is required as soon as the best estimate of the system's reliability, following from the best estimate of the return period of the CDS (Eq. (1)), falls below the pre-defined reliability standard. This simplified example illustrates that due to rainfall variability the timing of re-investment in the system cannot be assumed to be known if a reliability standard has to be met. Future beliefs about the return period of rainfall extremes are partly based on new rainfall observations and may result in under- or overestimation of the *actual* flood probability, and hence in over- or

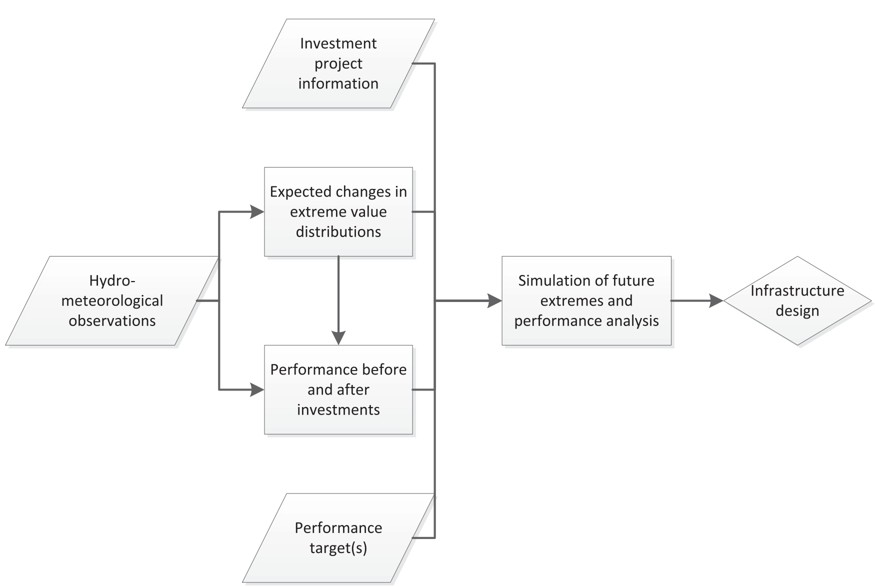

Fig. 1. Flowchart with required inputs (trapezoids) and processes (rectangles) for decision-making on cost-effective infrastructure design.