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Simulating flood risk under non-stationary climate and urban development conditions — Experimental setup for multiple hazards and a variety of scenarios

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A B S T R A C T

A framework for assessing economic flood damage for a large number of climate and urban development scenarios with limited computational effort is presented. Response surfaces are applied to characterize flood damage based on physical variables describing climate-driven hazards and changing vulnerability resulting from urban growth. The framework is embedded in an experimental setup where flood damage obtained from combined hydraulic-urban development simulations is approximated using kriging-metamodels. Space-filling, sequential and stratified sequential sampling strategies are tested. Reliable approximations of economic damage are obtained in a theoretical case study involving pluvial and coastal hazards, and the stratified sequential sampling strategy is most robust to irregular surface shapes. The setup is currently limited to considering only planned urban development patterns and flood adaptation options implemented over short time horizons. However, the number of simulations is reduced by up to one order of magnitude compared to scenario-based methods, highlighting the potential of the approach.

1. Introduction

Flood risk in cities is strongly affected by climate change and urban development (Hinkel et al., 2014; Muis et al., 2015; Muller, 2007; Semadeni-Davies et al., 2008; Zhou et al., 2012). The planning of flood risk adaptation measures therefore often relies on projections of these factors. However, both projections of climate (Hall et al., 2014; Madsen et al., 2014) and urban development (Cohen, 2004; Granger and Jeon, 2007) are subject to significant uncertainties. The design of flood adaptation options should therefore consider a variety of scenarios to identify robust measures and to identify opportunities to adapt options over time (Walker et al., 2013) and thus to gain the trust of decision makers (Leskens et al., 2014). Scenarios are in our case defined as changes of external circumstances that cannot be affected by the decision maker, i.e., different realisations of how climate and urban population develop over time.

To compare the efficiency of different adaptation measures, economic tools such as cost-benefit analysis are typically applied (GIZ, 2013). For a single scenario, the benefit from flood adaptation is the reduction in expected damages *ED* (Löwe et al., 2017), which can be assessed by integrating expected annual damages (*EAD*)

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(USACE, 1989) over the planning horizon. Depending on the considered scenario, *EAD* will often change in a nonlinear way with time. Consequently, *EAD* needs to be evaluated for multiple time points (Fig. 1) to be able to perform numerical integration over the planning horizon (Löwe et al., 2017; Zhou et al., 2012). Similarly, the dimension and complexity of investment decisions in flood risk adaptation often means that we are also interested in the advantages and disadvantages of postponing the implementation of adaptation measures into the future (Watkiss et al., 2015) and in identifying tipping points, i.e., time points where critical values of flood risk are exceeded (Kwakkel et al., 2016). Also these analyses require an evaluation of *EAD* at multiple time points in the future, which then needs to be repeated for each scenario that is considered.

Detailed hydraulic simulation models are the standard tool to assess flood hazards in urban areas (Chen et al., 2012a; Şen and Kahya, 2017; Velasco et al., 2015). A number of setups have also considered the impact of urban development on urban water systems and flood hazards (Doglioni et al., 2009; Huong and Pathirana, 2013; Sekovski et al., 2015; Urich and Rauch, 2014). Löwe et al. (2017) presented a framework that automatically links the output of an agent-based urban development model to a 1D-2D hydraulic model. This setup is illustrated in Fig. 2 and forms the point of departure for this paper. It simulates flood risk for a user-selected planning option, defined by a set of water management measures implemented in the hydraulic model and an urban planning policy (i.e., the location and form in which urban development should occur), and a user-selected scenario, defined by assumed rates of change for climate and population. *EAD* is assessed for multiple time points along the planning horizon as illustrated in Fig. 1. The simulation proceeds by

- Simulating urban development, i.e., creating new and replacing existing buildings based on the assumed population growth rate and the assumed development pattern, see Urich and Rauch (2014) and Appendix 1.
- Updating the 1D-2D hydraulic model with the simulated land-use layers. A separate hydraulic model is created for each time point along the planning horizon where *EAD* should be assessed.
- Performing 1D-2D simulations for multiple events corresponding to a relevant set of return periods for each of the considered time points for one or more hazards. In these simulations, pluvial risk is currently considered in the form of spatially uniform design storms, which is the standard approach in urban flood risk assessment. The simulated flood map is intersected with the simulated land-use layers and damages are computed based on depth-damage functions.

The drawback of the detailed simulation setup is the computational demand, in particular when we consider that EAD needs to be assessed for a variety of adaptation measures, multiple scenarios, and several time points within each scenario. Even in a simple study considering only one hazard Löwe et al. (2017) still performed more than 12,000 detailed simulations. Numerous methods for speeding up both hydraulic (Chen et al., 2012b; Davidsen et al., 2017; Guidolin et al., 2016) and urban development simulations (Jantz et al., 2010; Mikovits et al., 2015) have therefore been presented in the literature. These approaches typically attempt to simplify the way the relevant processes are simulated, while still preserving some form of physical representation of the system.

In the work presented here, we instead focus on reducing the number of detailed simulations by using metamodels (also denoted surrogates or emulators) for the computation of flood damages. Metamodels have previously been applied in hydrology to model physical variables such as flows (Machac et al., 2016; Wolfs et al., 2015) or, as in our case, "hyper-variables" such as flood damages (Yazdi and Salehi Neyshabouri, 2014). A comprehensive review was performed by Razavi et al. (2012a). Most applications in water-resources have considered problems related to optimization, where the meta-model is used to guide the optimizer to the optimum and the original model is then used to evaluate the objective function at the optimum. Further, in some cases (e.g., Borgonovo et al. (2012)) meta-models were applied for the computation of sensitivity indices.

Our work instead uses metamodels to characterize the flood response of a catchment, i.e., the economic flood damages observed in the catchment given a certain magnitude of (multiple) flood hazards, and given a vulnerability of the catchment defined by the

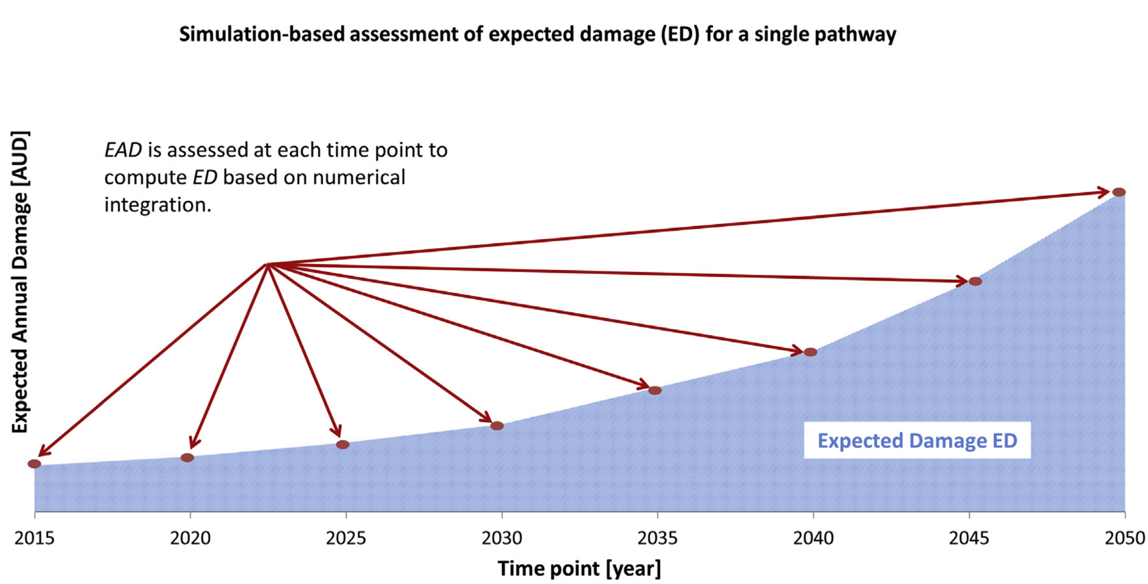

Fig. 1. Illustrative development of expected annual damage (EAD) over the planning horizon for a single scenario, defined by assumptions on climate change rates and urban growth rate and assuming that a fixed set of water management options and urban planning policies is implemented.