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The impact of the uncertainty of dike breach development time on flood hazard

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Abstract

The impact of uncertainty of dike breach development time on breach probabilities of downstream dikes and flood hazard was investigated by means of a Monte-Carlo-based probabilistic-deterministic flood hazard model. Three scenarios of breach development time were compared — one fixed-time scenario and two scenarios with stochastically generated breach development time. For the latter two scenarios, the dependency between the ultimate breach width and breach development time was modelled using a fully-dependent and a fully-independent copula. The simulation results suggest that in view of uncertainty in the flood hydrograph shape, dike breach locations, breach points in time and ultimate breach widths, the uncertainty due to the dike breach development time and dependence structure with the ultimate breach width should not be neglected when simulating multiple interdependent breaches. A significant difference in dike failure probabilities was simulated for a number of dikes in a 100-year flood scenario. Large changes in flood hazard are, however, relatively unlikely for a selected river reach.

Keywords: flood hazard, dike failure, breach development time,

uncertainty

1. Introduction

Assessments of flood hazard and risk, which systematically consider various uncertainty sources, have become the state-of-the-art approaches. They acknowledge enormous uncertainties associated with model parameters, constraining observations and natural variability of flood processes (Aronica et al., 2002; Apel et al., 2004; Dawson et al., 2005; Apel et al., 2009; Vorogushyn et al., 2010). Failures of defence systems are particularly poorly understood and formalized. Besides the uncertainty in the limit state functions and their parameters, i.e. in the initiation of failure of a particular defence, e.g. dike, there are uncertainties with regards to the breach development process such as breach development time and final width. Uncertainty in the limit state functions has already been addressed by applying the concept of fragility functions. These functions indicate the failure probability of a dike depending on hydraulic load (Sayers et al., 2002; Apel et al., 2004; Dawson et al., 2005; Vorogushyn et al., 2009).

In flood hazard assessment studies of fluvial dikes, several approaches have been adopted to handle the breach morphology. Rather often breach width was considered in the form of scenarios, derived from past observations (Hesselink et al., 2003; Alkema and Middelkoop, 2005; Aureli et al., 2005). In the absence of observation evidence, assumptions from a physically plausible range were made. Apel et al. (2004, 2006) investigated 5 scenarios with breach widths ranging between 100 and 400 m and determined the impact in terms of breach probability reduction for a downstream dike using a dynamic-probabilistic model.

In several studies simple empirical models were used. Hall et al. (2003) employed a simple linear relationship between the ultimate breach width and dimensionless load multiplied by the defence length (Eq. 1).

$$B_w = 0.05xL_d, B_w \leq L_d \tag{1}$$

where B_w – ultimate breach width [m], x – dimensionless load [-], L_d – length of a defence structure/section [m]. Eq. 1 relates the breach width not directly to the load expressed as a water level but rather to the dimensionless load. H is given by the ratio of the return period of the actual load and design return period of a structure. Such a ratio implies the knowledge about the return period for the load at any dike section, if water level is explicitly simulated. The fact that the water level and corresponding return period are not linearly related further impedes the direct use of Eq. 1 in a dynamic model.

A further empirical rule, employed by Dawson et al. (2005) and Dawson and Hall (2006), was based on the cohesion property of the dike material. Eq. 2 relates the dike overtopping height in absolute terms to the ultimate breach width:

$$B_w = min[10h_oa, L_d] \tag{2}$$

where h_o – overtopping height [m], a – empirical coefficient ranging between 3 and 15 for cohesive and non-cohesive materials, respectively. The value of a=6 was adopted for fluvial dikes and a=12 for sea dikes. This rule is not applicable to breach mechanisms other than overtopping. Moreover, when compared to the data of Gocht (2002) for the breaches during the Elbe flood in August 2002, the method seems to considerably underestimate the breach width. There is even evidence of 1.5 m overtopping on the Elbe without dike breaching. This suggests that there exist other processes influencing dike stability which are not accounted for by overtopping height and cohesion.

The correlation between the final breach width and other influencing factors, such as the area of hinterland polders and the width of downstream outflow polder opening, was investigated by Horlacher et al. (2005) for breaches of Saxonian dikes during the Elbe flood in 2002. The results indicated no correlation between the analyzed data. The knowledge about the factors influencing the breach width remains limited. The problem is further aggravated by the small number of breach events and their often poor documentation. However, the recently acquired data stock for the Elbe 2002 flood (Gocht, 2002; Horlacher et al., 2005) allowed the breach width modeling to be addressed in a probabilistic way by fitting a log-normal probability distribution function to the empirical distribution (Vorogushyn et al., 2010).

Breach growth appears to be non-linear. One distinguishes between the rate of headcut migration in case of overtopping, breach deepening and widening rates. In small-scale experiments with a dam of 0.9 m height and 1 m^3 s^{-1} overtopping discharge, Hahn et al. (2000) observed a 5-fold increase in the headcut migration rate over time. The authors measured rates ranging between 0.47 m h^{-1} to about 2.1 m h^{-1}. The headcut migration rate depends on the erosion stage starting with the surface erosion due to overtopping sheetflow, progressing into cascading overfalls and ending up with a single headcut. When the breach is completely developed in the vertical direction, the widening process can further progress triggered by water flow through the breach. The rate of breach growth varies dramatically, according to the experiments of Hahn et al. (2000) by as much as 60-fold, depending on the dike material ranging from sandy and silty to clayey soils.

In the large-scale embankment failure tests accomplished in the IMPACT project (IMPACT, 2001), typical durations for development of approximately 30 m wide breaches ranged between 5 and 10 minutes for rockfill dams to 1 hour for clayey dams. For the silty moraine core dams about 20 minutes were required for breach development (Vaskinn et al., 2004). On the other hand, there exists evidence of non-gradual breach development, e.g. when the whole clayey dike section of 190 m was flushed away in a few seconds (Hesselink et al., 2003).

While there was progress in understanding the breaching process for non-cohesive dikes, the erosion of cohesive material remains poorly understood (Broich, 2003). Ironically, the majority of breached dikes (95%) during the Elbe 2002-flood in Saxony were constructed out of cohesive material (Horlacher et al., 2005).

The reviewed experimental studies indicate a strong variation of breach development rates, which makes the modelling of breach growth a highly complex task. Over the past four decades only moderate progress has been achieved concerning a sound simulation of breach development in fluvial dikes. Singh (1996) provides a comprehensive overview of the currently available empirical and analytical models of dam breaching that vary considerably in terms of data requirements and complexity. However, predictions of breach development time remain highly uncertain ($\pm$ 1 order of magnitude) (Wahl, 2004).

In the scope of reach-scale flood risk analyses, breach development times were often considered as deterministic variables neglecting the effect of their variability. Some authors considered instantaneous breaching (Di Baldassarre et al., 2009, 2010), others adopted fixed values between 1 and 3 hours (Han et al., 1998; Apel et al., 2004; Alkema and Middelkoop, 2005; Vorogushyn et al., 2010). It was hypothesized that the breach development time did not significantly influence the flood hazard indicators. This assumption was confirmed by the sensitivity analyses for a single breach case (Chatterjee et al., 2008; Di Baldassarre et al., 2009). However, in case of modelling mutually dependent multiple breaches, the breach development time may influence the hydraulic load on downstream dikes and finally affect the breach probabilities and spatial fields of hazard indicators. In this paper, we systematically investigate the impact of breach development time on flood hazard for systems of multiple breaches and compare them with other uncertainty sources such as flow hydrograph shape, dike failure location, time and breach width.

2. Methodology

We apply the probabilistic-deterministic modelling system IHAM (Vorogushyn et al., 2010) on an about 90 km long Elbe River reach (Figure 1). IHAM combines a 1D model for the river channel hydraulics (USACE, 1995), a probabilistic dike breach model for overtopping, piping and slope instability due to the seepage flow (micro-instability), and a 2D storage cell inundation model for floodplain flow in case of dike breaches. All three models are interactively coupled and run in a Monte Carlo simulation framework. The 1D model continuously simulates the water level and discharges along the

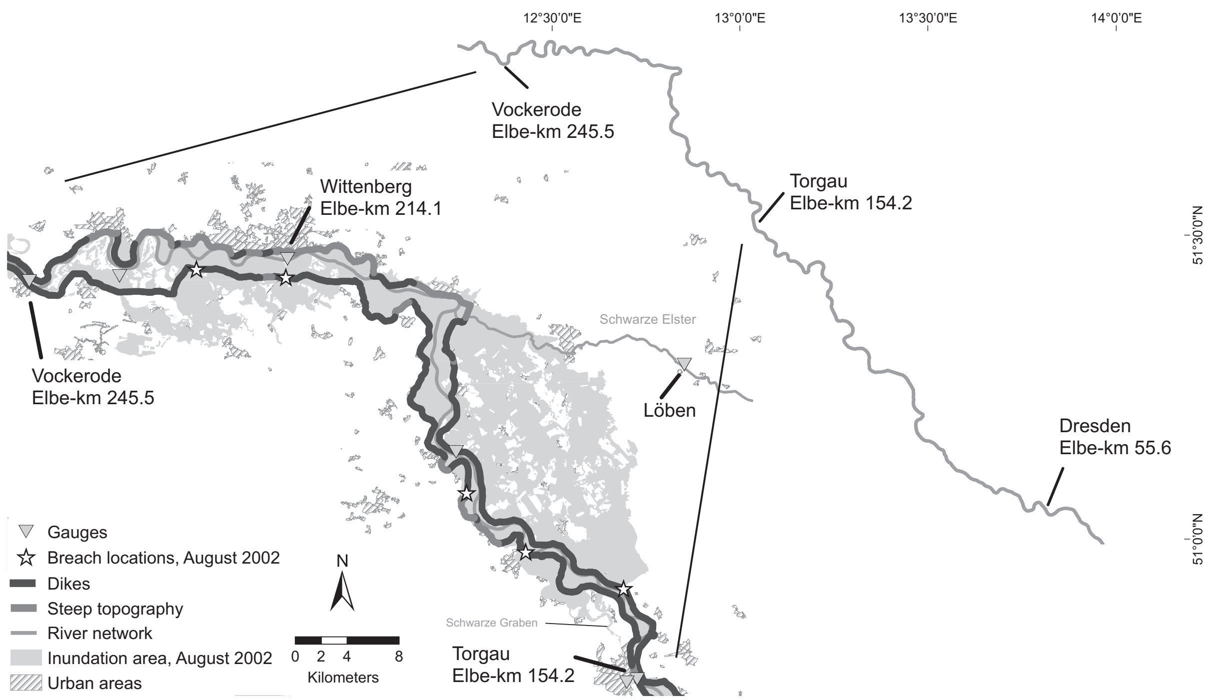

Figure 1: Study area along the Elbe River reach between gauges Torgau and Vockerode.

river trajectory. Those determine the hydraulic load on flood protection dikes. Each discretized dike section is successively tested for failure due to the three mentioned breach mechanisms at fixed time intervals. The failure probability of a dike section is computed based on the fragility functions for each breach mechanisms and the current load. In case of a dike failure, the ultimate breach width is stochastically modelled. The breach outflow entering the dike-protected floodplain is further distributed by the 2D inundation model. IHAM originally considers the following sources of uncertainty within a Monte Carlo framework:

- shape of inflow hydrographs. We considered five typical hydrograph forms for a 100-year flood event of 30 days duration at gauge Torgau. These hydrographs were derived from the cluster analysis of historical hydrographs.

- dike breach location and breach point in time. Those are determined at runtime based on fragility curves for each dike segment and simulated hydraulic load.

- dike breach width (B_w). This is modelled stochastically based on the truncated log-normal distribution LN($\mu_{ln} = 3.77$, $\sigma_{ln} = 0.86$) fitted to the empirical distribution (Vorogushyn et al., 2010). If a dike failure is simulated during a model run, the value for the ultimate breach width is randomly sampled from the defined distribution function.

A detailed description of the modelling system is provided in Vorogushyn et al. (2010). As a result, IHAM computes dike hazard maps that indicate dike failure probabilities for each discretized dike section as a proportion of simulated failures to the total number of the Monte Carlo runs. Furthermore, IHAM computes probabilistic flood hazard maps that represent, for example, maximum inundation depths for the flooded areas. From the Monte Carlo runs, the median and percentile maps can be derived and indicate the uncertainty range for each inundated raster cell.

In this paper, we extended IHAM in order to consider the uncertainty in breach development time (B_t). A previously applied constant value of one hour was substituted by a probability distribution function of breach development time. Unfortunately, the empirical basis for deriving the probability distribution is extremely scarce and is limited to the studies mentioned in the literature review. We therefore assumed the breach development time to be normally distributed with a mean of one hour. The adopted mean time corresponds to the experiments of Vaskinn et al. (2004) for comparable soil types as found in the Elbe dikes. Taking into account the historical evidences (Hesselink et al., 2003; Alkema and Middelkoop, 2005), we truncated the normal distribution at 15 minutes and 3 hours representing the lower and upper boundaries, respectively. The standard deviation was assumed at $\sigma = 1.5$. The breach grows gradually within the breach development time till the ultimate width. The historical and experimental evidence suggest that breach development time might depend on the final breach width with the tendency of longer development times for larger breaches, although there exist some outliers. The dependence structure is unknown. Therefore, we considered two extreme cases. We modelled the dependence structure of two variables assuming full dependence and full independence using a copula approach.

Assuming a bivariate distribution of B_w and B_t denoted as $F_{XY}(B_w, B_t)$, there exist a 2-copula $\mathbf{C}$ such that

$$F_{XY}(B_w, B_t) = \mathbf{C}(F_X(B_w), F_Y(B_t)) : [0, 1]^2 \tag{3}$$

where $F_X(B_w) = \text{LN}(\mu_{ln} = 3.77, \sigma_{ln} = 0.86)$ and $F_Y(B_t) = \text{N}(\mu = 1, \sigma = 1.5)$ represent the marginal distributions of breach width and development time, respectively. Assuming a fully dependent structure of two random variables, the pairs of breach development time and width are fully concordant and their corresponding copula is given by

$$\mathbf{C}(F_X(B_w), F_Y(B_t)) = min\{F_X(B_w), F_Y(B_t)\} \tag{4}$$

known as the Fréchet-Hoeffding upper bound copula. Contrary, in the case of full independence, the dependence structure is described by the independence copula

$$\mathbf{C}(F_X(B_w), F_Y(B_t)) = F_X(B_w) \cdot F_Y(B_t) \tag{5}$$

Note, in the mathematical sense the fully independent copula does not represent the extreme case of dependence. Those are given by the Fréchet-Hoeffding lower and upper bound copulas, with former describing the fully negative dependence. In our case, however, the fully negative dependence between breach width and breach development time seems to be unrealistic.

The simulation of respective random pairs of B_w and B_t was carried out as proposed by e.g. Salvadori et al. (2007). First, the random variable u is generated uniformly on $[0, 1]$. Further, v is computed as the inverse of the conditional form of the copula

$$v = c_u^{[-1]}(u), \text{ where } c_u(v) = P\{V \leq v \mid U = u\} = \frac{\partial}{\partial u}\mathbf{C}(u, v) \tag{6}$$

Finally, B_w and B_t are computed from the quasi-inverses of the marginal distributions

$$B_w = F_X^{[-1]}(u),\ B_t = F_Y^{[-1]}(v), \tag{7}$$

Practically, for the case of full dependence $u = v$, and for full independence u and v are generated randomly and uniformly on $[0, 1]$. We compared the simulated dike breach probabilities and inundation hazard in terms of maximum inundation depth for the two scenarios with stochastic breach development time and using a fixed B_t of 1 hour.

3. Results and discussion

In total, 1000 Monte Carlo runs were carried out for each scenario to derive dike and flood hazard maps. The convergence of dike breach probabilities is expected to be in the range of $[-3, +3]$ % *points* for this reach and a 100-year flood (Vorogushyn et al., 2010). Note that the convergence of the results is determined by the floodplain storage capacity related to the total flood volume, i.e. the higher the storage capacity, the higher is the potential of dike breaches to redistribute the limited flood water volume along the reach and thus affect the failure frequencies. Therefore, both the study reach and the return period are decisive for convergence. Figure 2 indicates the differences in failure probabilities between the scenarios with predefined dependence structure and a fixed time scenario. It can be observed that the differences are mostly enclosed in the envelope of convergence. However, for a few right-side dike sections a remarkable decrease in failure probability (up to 20 % *points*) was simulated for the scenario with full dependence. In the scenario with fully independent breach width and breach development time

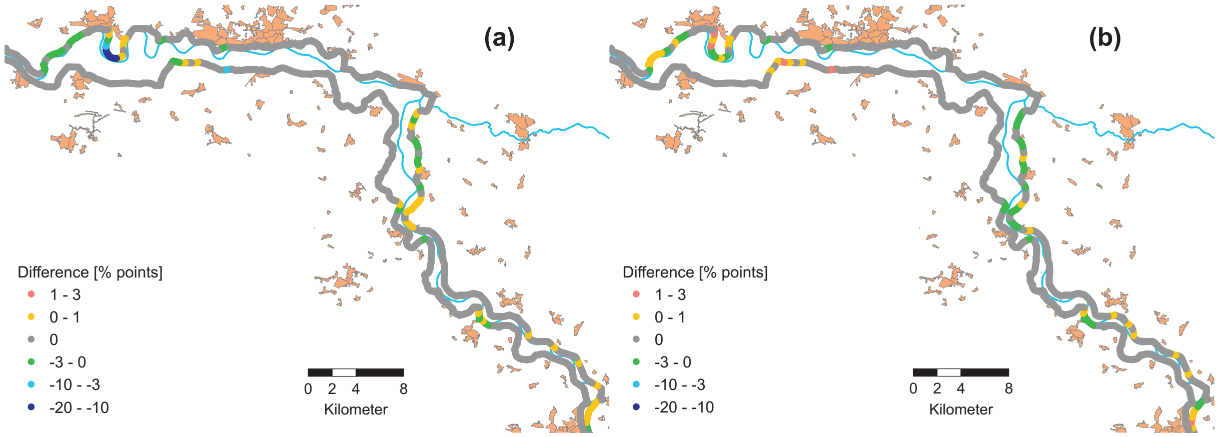

Figure 2: Comparison of dike breach probabilities along the study reach between the scenario (a) with fully dependent breach width and breach development time and fixed time and (b) with fully independent breach width and breach development time and fixed time.

such a behaviour was not simulated (Figure 2b).

An inspection of the corresponding channel flow hydrographs for the 10^{th} and 90^{th} percentiles (Figure 3) near the point of interest (Elbe-km 236.5) revealed a stronger capping of the hydrographs for the scenario with full dependence, increasing towards high percentiles. Whereas the hydrographs of fixed-time and full-independence scenarios slightly deviate from each other, the hydrograph for the full-dependence scenario is significantly buffered, particularly around the peak flows.

To shed light on this behaviour, we had a closer look at the difference in maximum inundation depths between the full dependence and the fixed time scenarios (Figure 4). It appears that the maximum depths in the area slightly upstream of the dike sections with decreased failure probability increased by a few centimeters for the 10^{th} percentile (Figure 4a). For the

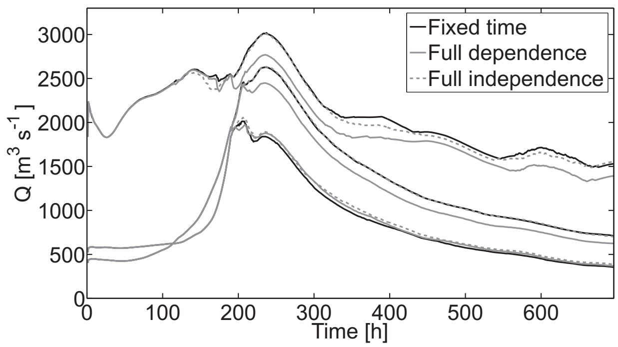

Figure 3: 10^{th} and 90^{th} percentiles as well as median discharge for three scenarios at Elbe-km 236.5.

90^{th} percentile, there is generally a decline in maximum inundation depths in the downstream part of the reach, whereas upstream of the tributary inflow there is a considerable increase in inundation depths (Figure 4b). These results suggest that the change in failure probabilities of dikes can be caused by two reasons. For the lower percentiles in the full-dependence scenario, the outflow through the dike breaches on the opposite river side increased slightly causing the hydrograph dampening (Figure 3 and Figure 4a). For the higher discharge percentiles, the areas farther upstream became more inundated and functioned as a buffer for high flows. Both effects led to the load relaxation downstream. A few particularly sensitive dike sections exhibited lower failure probabilities as a consequence.

The stochastic breach development time and the full dependence structure appear to be able to systematically alter the breach outflow discharge compared to the fixed time scenario. In the full dependence scenario, the narrower breaches develop faster, those wider than mean ones slower. It appears that the breach development time is a constraining factor for the outflow discharge

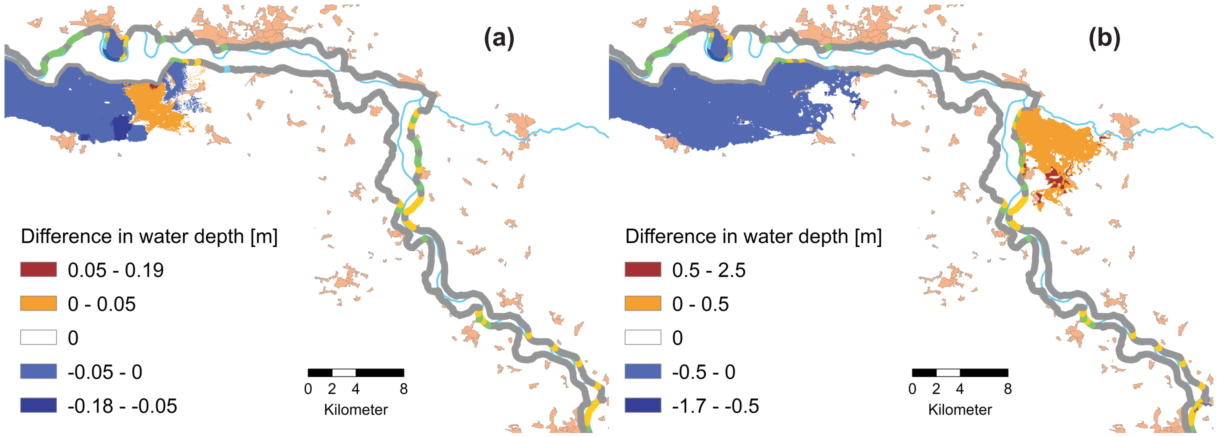

Figure 4: Comparison of scenario with full dependent breach width and breach development time and scenario with the fixed breach time for (a) the 10^{th} percentile and for (b) the 90^{th} percentile of the maximum inundation depths.

for the narrower breaches. For the wider breaches, the constraining topography of the floodplain and the channel flood volume do play a greater role. At locations with a high storage capacity, the stronger outflow may dampen the channel hydrograph peaks and affect the sensitive dikes downstream. In our case, the changes in dike failure probabilities of downstream dike sections did not result in the significant reduction of maximum water depths. These dike sections protect a topographically constrained floodplain area which becomes inundated also due to failure of other dike sections. However, for other river reaches, a change in failure probability and river discharge may result in decreased hazard.

4. Conclusions

We investigated the possible impact of stochasticity in dike breach development time on flood hazard along a diked river reach considering multiple interdependent dike breaches. Flood hazard was assessed in terms of dike breach probability and maximum inundation depths. Based on empirical evidence, we assumed a plausible probability distribution function of dike breach development time. Using a copula approach, two scenarios of dependence structure (full dependence and full independence) between the dike breach width and breach development time were defined. Simulation results of two scenarios were compared with those computed with the fixed breach development time of one hour.

Comparisons of simulated failure probabilities and maximum inundation depths revealed a drop of failure probabilities (up to 20 % *points*) for a number of dike sections in case of the scenario with the full dependency of breach width and development time. This scenario seems to be plausible. The stochasticity of breach development time and dependence structure are capable of influencing the breach outflow discharge and may alter the load on downstream dikes. We conclude that in view of uncertainty in input flood hydrograph shape, dike breach location, breach point in time and ultimate width, the breach development time and the dependence structure between the development time and ultimate breach width can significantly impact the dike failure probability. For high discharge percentiles in a 100-year flood scenario, a change in maximum inundation depths was simulated. Only for higher percentiles significant changes in flood hazard were detected. Such large changes (above 0.5 m) are relatively improbable. In the areas, which are protected by dikes that exhibited strong a reduction in failure probability, only insignificant changes in hazard were simulated. This is explained by the strong constraining effect of the surrounding topography, which controls inundation. Nevertheless, we to consider the uncertainty in breach development time in modelling studies with interdependent dike failures. For other river reaches and/or flood magnitudes different dike sections may experience failure probability changes. This may lead to significant changes in flood hazard. The experimental, observational and modelling basis for deriving the breach development times and dependence structure needs to be further advanced as currently only very limited information about breach development is available.

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