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Is probability of peak discharge a suitable proxy for probability of damage in flood risk analysis?

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Extended Abstract:

INTRODUCTION

Flood risk is expected to rise as a consequence of global change which is driven by changing climate and changing vulnerability (Bouwer, 2010; Mohleji and Pielke, 2014). It is widely accepted that there is a need for regional flood risk analysis frameworks which enable the spatially coherent assessment of flood risk and its changes (Mechler and Bouwer, 2014). Basically, flood risk is defined as the probability of suffering damage or loss. As observations of damage are sparse, the probability of damage can hardly be derived directly from loss records.

The assignment of probability to a flood event is a complex task since floods are the outcome of a combination of random processes (Grünewald, 2001) such as for instance rainfall, catchment wetness and river state (Merz, 2006). Traditionally the estimation of flood probability in risk analysis is either based on (i) the design rainfall approach using intensity duration frequency curves as input for event based hydrologic simulations or (ii) based on statistical analysis of block maxima or peaks over threshold in a time series of observed discharges at a gauging station situated nearby. The return period of a flood peak is then used as a proxy for the probability of consequences. On that note, the T-years flood discharges derived from these statistics are used to estimate inundation extent and depths, to analyse vulnerability and finally to determine risk assuming a similar probability for peak discharges, inundation depths and consequences.

Both approaches are problematic. The assumption that the return period of the flood discharge corresponds to the return period of the rainfall is not generally valid because both rainfall characteristics and catchment state influence the discharge response (e.g. Paquet et al., 2013; Haberlandt et al., 2014). Objections concerning the validity of using the flood peak probability as a proxy arises firstly from the marked spatial heterogeneity of flood event characteristics particularly in larger areas (Keef et al., 2009; Thieken et al., 2014) and secondly from the non-linear transformation of discharges to water levels and further to flood damage.

In this study, we scrutinize the appropriateness of using flood peak probability discharge as a proxy approach by comparing the outcomes in terms of risk curves to the direct statistical analysis and frequency estimation of flood damage. Further, we examine the differences in flood risk on various spatial aggregation levels underlying the frequency analysis of flood peaks and flood damage.

METHODS

Models

For our analysis we use the regional flood model (RFM) developed by (Falter et al., 2014a) which enables a continuous simulation of the entire flood risk chain using a series of coupled models including hydrological, 1d-hydrodynamic and 2d-inudation processes as well as flood damage estimations (see Figure 1). In this study RFM is driven by synthetic meteorological input data produced by a multi-site multi-variate weather generator (Hundecha and Merz, 2012) which provides spatially consistent realisations of meteorological fields for large areas. Hydrological simulations are carried out on a daily basis using the eco-hydrological model SWIM (Krysanova et al., 1998). Flood routing in the river network is represented by a 1D diffusive wave equation. When the water levels in the rivers exceed the dike crests, outflow to the hinterland occurs which is taken into account as a point source boundary condition for the 2D hinterland inundation model. The 2D inundation model uses a raster-based inertia formulation (Bates et al., 2010). For each flood event causing hinterland inundations grids of maximum water levels in each cell are extracted. The coupling of 1D and 2D models accounts for the feedback effect of hinterland water levels. The maximum water level grids are input for the multi-variate flood loss model FLEMOps+r (Elmer et al., 2010) which calculates direct damage to residential buildings in each grid cell. For further details on the input data and the model implementation refer to (Falter et al., 2014a, 2014b).

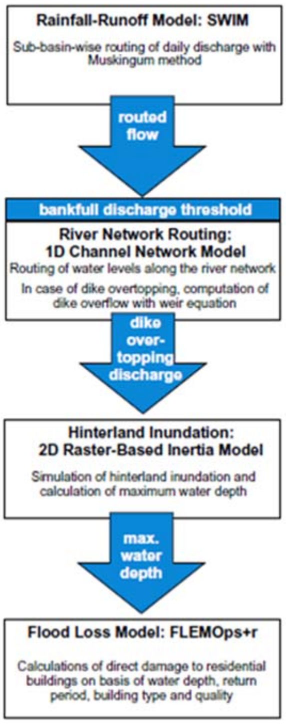


Figure 1. Components of the RFM model chain based on Falter et al., (2014)

Risk Analysis

The RFM simulation framework enables us to conduct long-term continuous simulations and thus provides the basis for statistical frequency estimations based on simulations results. As RFM covers the entire risk chain, samples of model outcomes are available for each component of the model cascade, i.e. discharges, water levels and damage in high spatial resolution. This data base allows us to compare the outcomes of flood risk assessment between the traditional proxy approach based on probability of flood peak discharge where Flood Risk = Probability (Discharge) x Damage and the direct estimation of probability based on a statistical analysis of flood damage where Flood Risk = Probability (Damage) x Damage.

Further, the spatial detail of the information available provides insight to different levels of spatial aggregation for flood risk analysis. In this regard we compare flood risk assessment on regional, local and in-situ levels.

APPLICATION FRAMEWORK

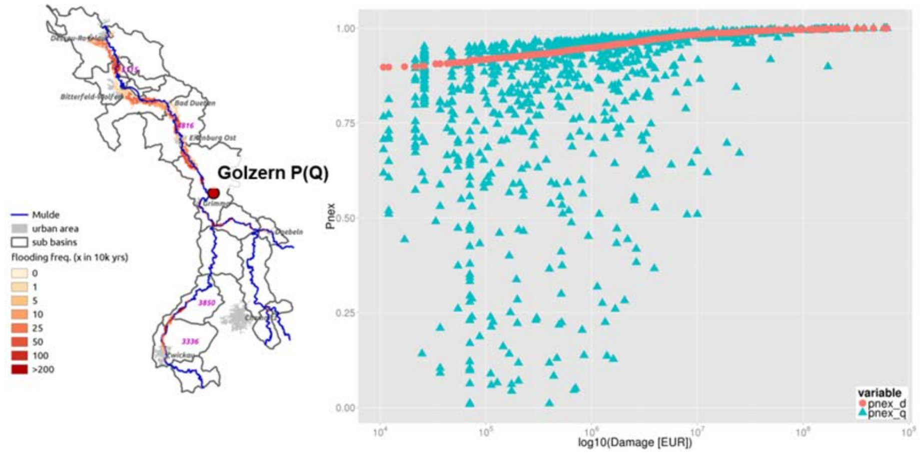
The RFM chain is set up in the Mulde River basin (AE = 6,000 km^2) a tributary to the Elbe river in Germany. The study area is divided into 19 sub-basins for hydrological simulations. The river network considered in the study region has a length of 380 km and the spatial resolution used for inundation modelling and damage estimation is 100 x 100 m.

The set-up of the model chain in the study region has been evaluated in the period from 1951 to 2003 with observed data where possible. The runoff simulation with SWIM indicates a reasonable simulation especially for high flows yielding modified Nash-Sutcliffe efficiency values (Hundecha and Bárdossy, 2004) of 0.82 to 0.86 for different gauges. The simulation of flood peak water levels with the 1D-hydrodynamic model yields peak errors in the range of 0.18 to 0.56 m. This is in the range of accuracy of dike crest height data which determines overtopping. For large-scale flood risk analysis this performance level can be considered acceptable. The evaluation of the 2D inundation model and the flood loss model is hardly possible. From the entire simulation period, observed flood inundation extends are only available for the August 2002 flood which caused wide-spread inundations mainly due to dike breaches. However, this inundation pathway is not yet implemented in RFM, and thus the location, the extent and inundation depths of simulated inundations for this particular event differ considerably from the observed flood extent. This is reflected in an agreement of observed and simulated flooded areas of 50 %. The damage model underestimates officially reported damage values by 70 %. This deviation is primarily related to the differences in inundated areas,

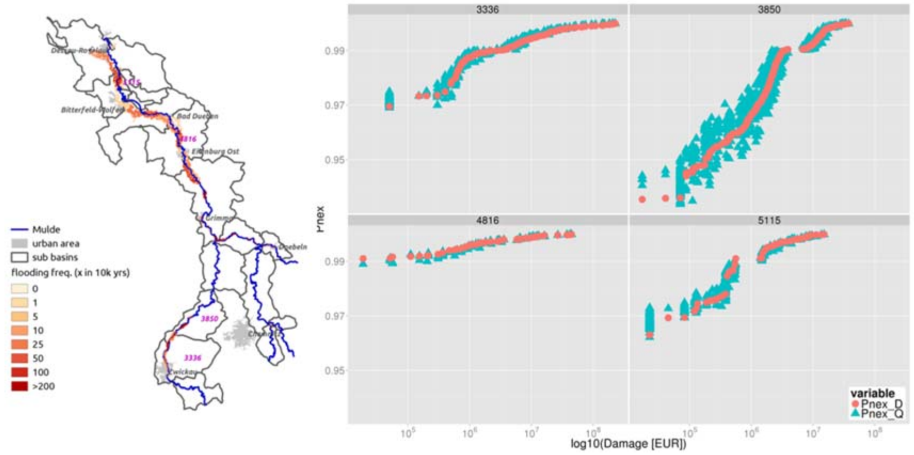
For the risk assessment RFM is driven by synthetically generated continuous daily climatology of 10,000 years length based on data for the years 1951 to 2003. The simulations with RFM result in ca. 2,000 flood events causing inundations. From this set of flood events 1,028 events have caused flood losses.

RESULTS

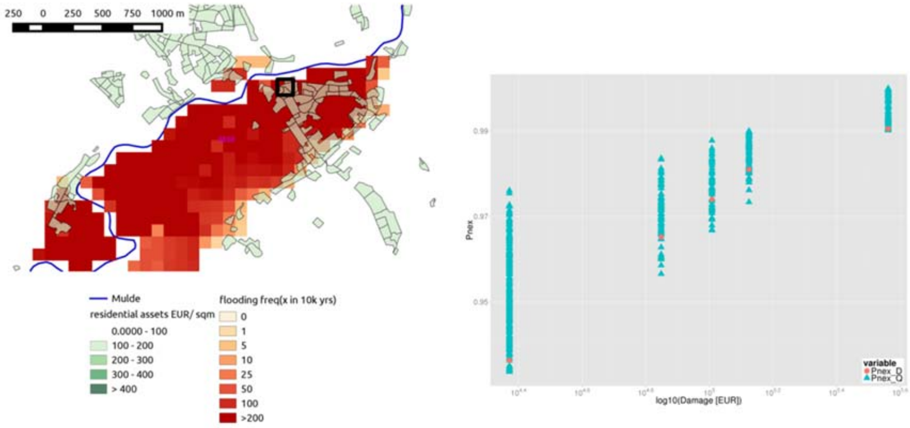
The estimation of non-exceedance probability of peak discharges probability (Pnex_q) within the traditional proxy approach is based on annual maximum discharge values from the 10,000 years continuous simulation period and is conducted for each SWIM sub-basin. The Generalized Extreme Value distribution is fitted to each sample using the method of L-Moments. The direct estimation of non-exceedance probability of damage (Pnex_d) is carried out by deriving the empirical distribution function from the sample of simulated flood loss on different spatial aggregation levels. On the regional level, flood loss is summed up for the whole study region. On the local level – represented by SWIM sub-basins – only the flood events that caused losses in the respective sub-basin area are considered. Sample sizes vary from sub-basin to sub-basin from 0 to 774 members.



(a) Regional flood risk



(b) Local flood risk



(c) In situ flood risk

Figure 2. Flood risk assessment on regional (panel a), local (panel b) and in-situ (panel c) aggregation levels using probability of discharges (blue) and probability of damage (red)

Empirical distributions are only derived if the sample size is larger than 30. On the in-situ level, i.e. the 100 x 100m gird cells, the sample is built up of the loss values available for each pixel. Due to local characteristics which control flow paths the sample sizes vary considerably on small scale. The results obtained from both approaches on the different aggregation levels are illustrated in terms of risk curves, i.e. probability of non-exceedance (Pnex) versus damage (in log scale) - in Figure 2.

In panel a (top) of Figure 2 the regional flood risk assessment is shown. For the traditional approach the GEV for the sub-basin which contains the gauge Golzern (for the location see the map on the left in panel a) is used as the reference for flood probability in the whole study region. Flood losses vary considerably within flood events of similar return periods and vice versa, variable probabilities are associated with similar flood losses. This emphasizes that the spatial variability of flood intensity in combination with heterogeneously distributed assets may cause highly variable damage. However, this variability seems to decrease for increasingly extreme events.

Panel b (mid) of Figure 2 compares the flood probability (Pnex_q) and probability of damage (Pnex_d) on the level of four selected SWIM sub-basins (for the locations see the map on the left in panel b). The variability of loss is clearly smaller than on the regional level which indicates a better representativeness of Pnex_q as a proxy for Pnex_d. Still, depending on the location of the basin, the relation of Pnex_q and damage is ambiguous. Disproportional increases in damage indicate that local inundation pathways which depend on the flood generation processes, the flood wave form and dike overtopping thresholds affect spatially distributed assets.

In panel c (bottom) of Figure 2 the flood probability (Pnex_q) on the level of SWIM sub-basins is compared with probability of damage (Pnex_d) in a selected pixel (marked as a black square) in sub-basin 3850 (cf. map on the left in panel b of Figure 2). The clustering of the results to different damage values stems from the classes of the flood loss model which differentiates damage according to building type, building quality, inundation depth and return period. In this application building types and building quality are invariable, and thus the variation in damage is determined by variations of inundation depth and return period. Again, the relation between Pnex_q and damage is ambiguous: a similar damage value is assigned a large variety of flood probabilities. The map extract on the left in panel c of Figure 2 illustrates the heterogeneous distribution of assets and the small scale variation of inundation characteristics. This emphasizes that flood risk varies also on small scale.

CONCLUSIONS

We examined the suitability of using the probability of flood peak discharge as a proxy for the probability of damage in flood risk assessment across a range of scales. Using the regional flood model RFM (Falter et al., 2014) which consists of a cascade of process based models including hydrological, 1D- and 2D hydraulic and flood damage models, the complete flood risk chain was continuously simulated over a virtual period of 10,000 years. The simulation results provide a unique data base to conduct a statistical analysis directly for flood damage. The results reveal a considerable variability in the relation between peak discharge probability and flood damage across the range of scales examined. Non-linearity and threshold behavior along the flood risk chain contribute to this variability. In this light, probability of flood peak discharge appears as a proxy that is associated with considerable uncertainty. Accordingly, one advantage of the RFM simulation framework is that flood risk can be calculated directly from damage simulation which circumvents the problems related to probability of flood peak discharges as a proxy. Further, the chain of process based models provides useful insights to spatial risk patterns. However, future advancements should target on an improved representation of local topography including flood protection measures and on the inclusion of dike breach mechanisms. The RFM simulation framework is suitable to investigate the implications of global change in terms of climate change scenarios and/or changes in vulnerability for future changes in flood risk.

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