Modelling dyke breaches and probable maximum flood in river catchments to reduce uncertainty in flood frequency analyses

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Abstract

Flood frequency analyses are often used as a basis for the design of flood protection measures. Since most discharge data cover only short durations of 50 years, there is a considerable uncertainty in characterising extreme events with return periods of 100 years or more. In addition, due to the non-constrained nature of the distribution functions, flood frequency curves are likely to overestimate the discharges for high return periods. Hence, additional methods can be incorporated to reduce the uncertainty in the flood frequency analysis and provide more accurate estimates of the design discharge. In this paper, two novel methods are introduced to reduce the uncertainty in estimating flood frequencies and producing more realistic flood frequency distributions: (i) inclusion of dyke breaches whereby the flood frequency distribution levels off to a discharge asymptote for extreme floods and (ii) calculation of a probable maximum flood which incorporates both hydrological and hydrodynamic modelling.

Introduction

Time series of river discharge at gauging stations are used as a basis for the design of flood protection measures. The maximum discharge used for the design specification is usually defined from flood frequency analyses in which a probability function according to exceedance probabilities or return periods (=1/exceedance probability) are fitted to the annual maximum discharges. Since most discharge data cover only short durations of 50 years, there is a large uncertainty in characterising extreme events with return periods of 100 years or more (Macdonald *et al.*, 2006). In addition, these flood frequency analyses do not incorporate failure of protection measures such as dykes. Hence, additional methods can be incorporated to reduce the uncertainty in flood frequency analysis and provide more accurate estimates of discharge design specifications. In this paper, two such methods are introduced to reduce the uncertainty in estimating flood frequencies: (i) inclusion of dyke breaches and (ii) calculation of a probable worst flood. Excerpts of this paper have been extracted from Michalek *et al*. (2007) and Michalek *et al*. (submitted).

Figure 1 shows theoretically how these two methods can be implemented to reduce uncertainty in the flood frequency analysis. Several probability functions can be drawn upon to fit discharge to return periods (or exceedance probabilities). These functions often coincide very closely for less extreme floods with return periods of less than 50 years. However, as shown in Figure 1, these diverge for extreme events greater than 100 years, making selection of the most appropriate function difficult and increasing the degree of uncertainty when extrapolating

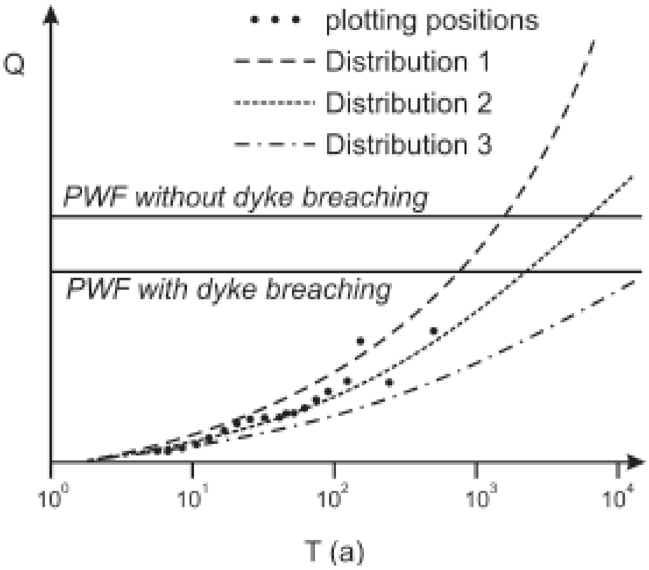

Figure 1 *Theoretical description of a flood frequency analysis showing the range of the probability functions used and the improvement in the statistics by simulating a probable worst flood event for an upper discharge bound and considering dyke breaches.*

the curves to very extreme events with return periods greater than 250 or 500 years.

For river stretches with dykes, the probability of dyke breaching increases with the extremity of the flood. Dyke breaching increases the retention area for flood water storage causing the distribution in flood frequency statistics to shift to lower discharges for extreme events (see Figure 1) (Apel *et al*., 2004). An approximate upper discharge bound can also be estimated using techniques such as: (i) probable maximum flood (PMF) which is simulated by combining the probable maximum precipitation (PMP) over a catchment with critical hydrological conditions, (ii) modifying the flood frequency analysis distribution function by increasing the skewness to a maximum value for floods with return periods greater than 500 years (e.g. see Kleeberg and Schumann, 2001) and (iii) calculating a worst flood based on observed extreme areal rainfall in combination with other hydrological extreme conditions, e.g. snowmelt (Harlin and Kung, 1992) or exceedingly high antecedent soil moisture conditions (this study). The latter approach is used in this paper with the upper bound providing an additional constraint on the frequency distribution in the flood frequency statistics (see Figure 1).

Incorporation of historical data is also a useful means of reducing uncertainty in flood frequency analysis (Thorndycraft *et al*., 2002). Such methods will not be considered in this paper but are worth mentioning briefly here. For instance, chronicles may provide insight on water levels and precipitation. Artworks may additionally provide estimates of water levels at certain locations for corresponding discharges from documented meteorological conditions. Gaps between these discrete events can be filled with duplicates of the existing gauge time series. Synthetic time series may also be generated to produce data to fill gaps. Hence, a much longer time series of annual maximum discharges can be incorporated to reduce the uncertainty in the ranges between the frequency distributions used.

Study site

The Mulde catchment is a sub-catchment of the Elbe River basin in south-eastern Germany. The southern boundary is marked by the mountain ranges of the Erzgebirge, which coincides with the Czech – German border. The catchment has a total area of 6171 km^2 (at the gauge Bad Düben). The elevation ranges from 52 m to 1213 m a.s.l., with approximately two-thirds of the area being lowlands and one-third mountains (500–1213 m a.s.l.) (see Figure 2). The mountain ranges in the south cause fast runoff responses to rainfall events in the tributaries, whereas in the major part of the catchment slower runoff responses dominate. The annual precipitation ranges from 500 mm in the lowlands to 1100 mm in the mountain ranges.

Methodology

Probable worst precipitation

We assume that the probable worst flood (PWF) can potentially be derived when two primary conditions are met as input to the hydrological model: (i) largest possible precipitation falling homogenously over the entire catchment area and (ii) highest possible antecedent soil moisture. From the analysis of observed precipitation in the Mulde catchment during the recorded period of 1951 to 2003, the extracted maximum sum of precipitation for three consecutive days was taken to create a homogeneous rain field for the synthetic probable worst precipitation (PWP). Three-day maximum summations were taken to extract events with the highest rainfall intensities, which was not necessarily obtained with 1-day or 5-day maximum summations. From the data series, events with the highest intensities occurred in the summers of 1954, 1983 and 2002. The centres of these precipitation fields were situated respectively in the western (1954), northern (1983) and eastern (2002) parts of the catchment (see Figure 3). While the 1954 and 2002 precipitation events were caused by low-pressure and trough weather systems over Central Europe (Vb-cyclone) (Petrow *et al*., 2007) with similar characteristics, the 1983 event was triggered by a north-easterly cyclone system. Had the centres of these events coincided with the centre of the catchment area, a precipitation field similar to our synthetic PWP may have occurred. The synthetic PWP was constructed so that the maximum precipitation within the three day periods of all 51 climate stations, from which the 3-day maximum summations were derived, all coincide with the same simulation day. All other meteorological parameter values are consistent with the corresponding day for which the precipitation value was taken.

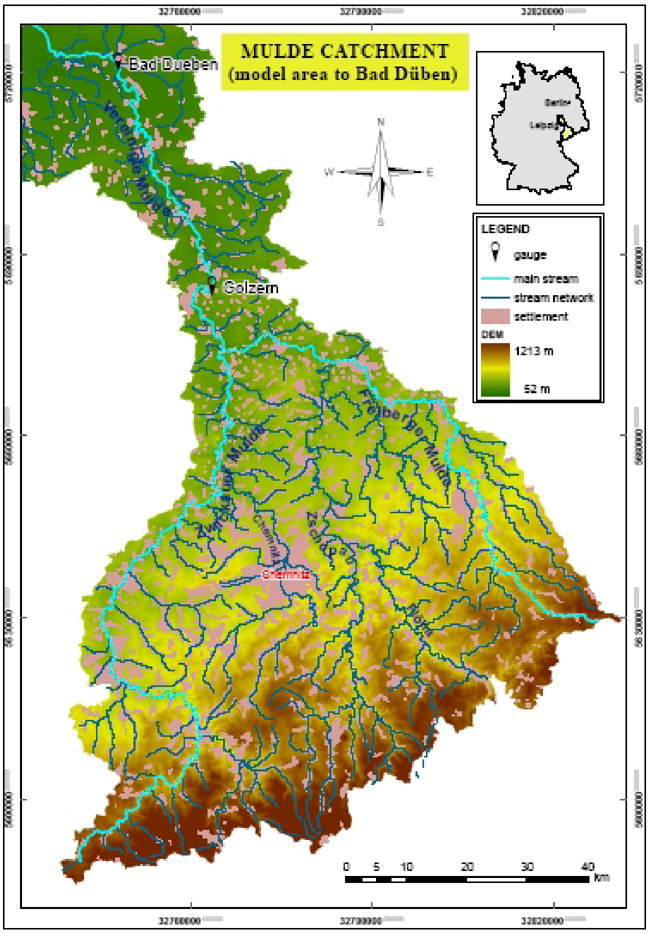

Figure 2 *The Mulde catchment in Germany*

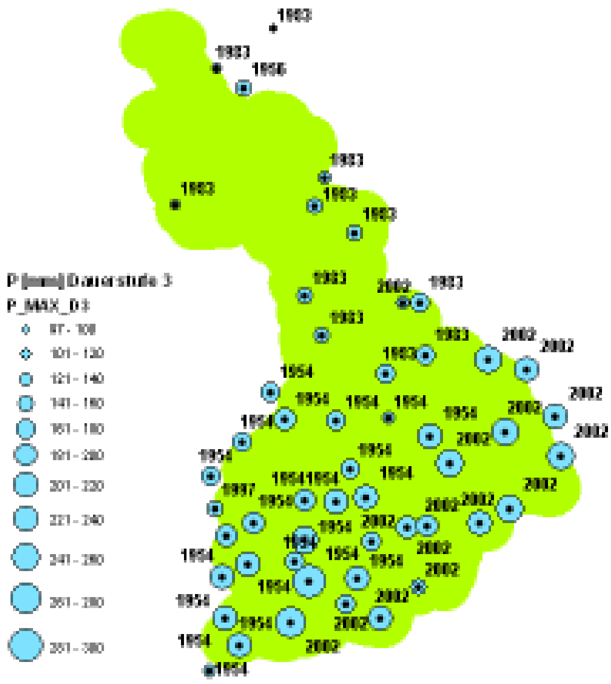

Figure 3 *Climate stations designated with the year of largest cumulative precipitation totals for three consecutive days.*

This proposed maximum precipitation field PWP, whose centre is aligned with the centre of the Mulde catchment, is an important input for the hydrological model. In conjunction with the highest soil moisture content simulated for the period 1951–2003, a maximum discharge at Golzern could be computed with the hydrological model which served as input to the hydrodynamic model.

Modelling system

The modelling system consists of four models (see Figure 4). The hydrological model J2000 (Krause, 2001) is used to simulate the runoff components to describe the precipitation runoff on the land surfaces. As flood events become more extreme, hydrograph routing of the generated runoff becomes increasingly important, especially in the lowland river reaches. For this, the 1D model EPDRiv1 (http://www.epdriv1.com) which uses the full dynamic wave equation, is implemented. A dyke breach model (Apel *et al*., 2004) predicts dyke failure on the basis of river water overtopping the dyke. In the event of a dyke breach, a 2D storage cell inundation model based on the diffusion wave equation (Merz, 1996) is executed to simulate the movement of water from the breach area into the hinterland. Since the dispersed water also affects the hydraulics in the river, there is an interactive linkage between the dispersion and routing components.

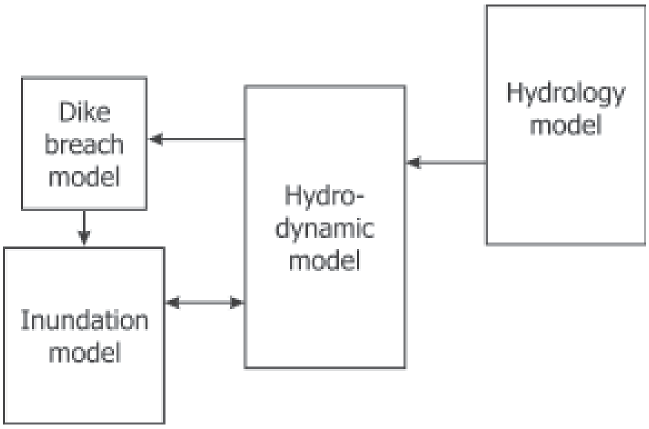

Figure 4 *The modelling system consisting of four models: hydrology, 1D river hydrodynamics, dyke breach, and 2D inundation.*

Results and Discussion

August 2002 flood simulation

Testing has already been undertaken for the hydrological model (Fleischbein *et al*., 2006) and the hydrodynamic model (Vorogushyn *et al*., 2007). Figure 5 shows the peak discharges recorded at the gauges of Golzern and Bad Düben (respectively the inlet and outlet points of the 1D hydrodynamic model domain). Three scenarios for routing the Golzern input hydrograph are simulated: (i) without dyke breaches, (ii) breaches of dykes with the maximum crest heights and (iii) breaches of dykes with the minimum crest heights. The first scenario serves to determine if the routing of the hydrograph along the reach is simulated properly without dyke breaches. The gauge readings of the peak discharges from Bad Düben lie within the range of the peak discharges obtained with dyke breaching, the larger peak discharges resulting from maximum dyke crest heights and the lower peak discharges from the minimum crest heights, showing a good plausibility of the computational results.

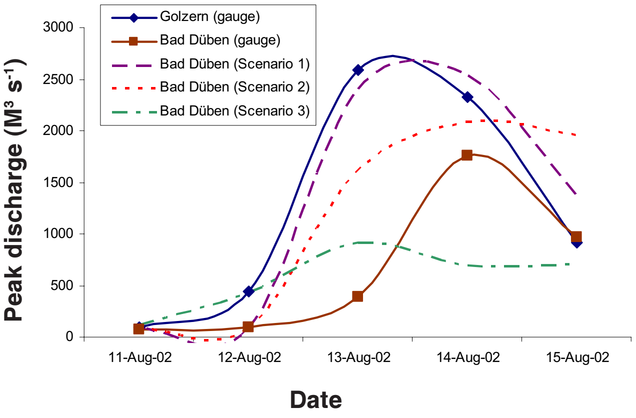

Figure 5 *Recorded and simulated peak discharges for the August 2002 flooding of the Mulde River using the modelling system.*

Probable worst flood with flood frequency analysis

Figure 6 shows the flood frequency analysis of the annual maximum discharges for the gauge readings taken at Bad Düben for the time series 1961–2003. The analysis was carried out with several typical distributions used to allocate discharges to return periods. Two PWF scenarios were simulated and superimposed on the distribution curves: (i) without dyke breaching and (ii) with dyke

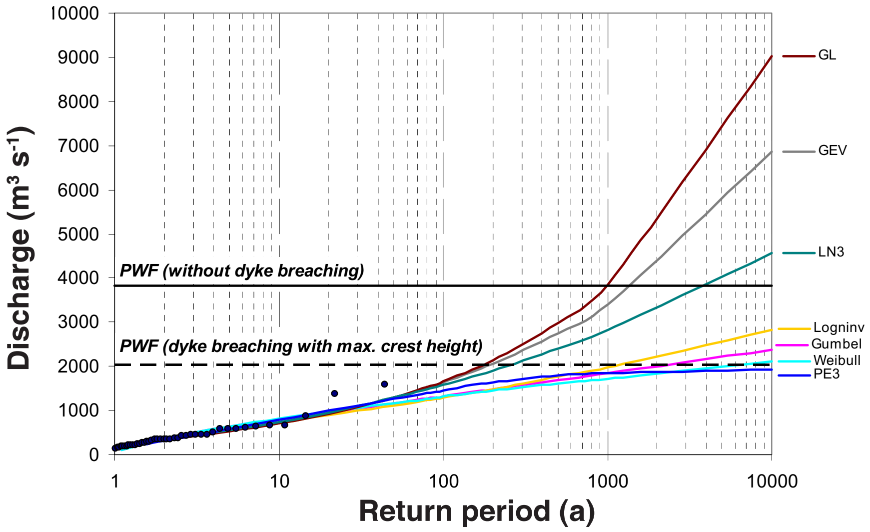

Figure 6 *Flood frequency analysis of the annual maximum discharges at the gauge at Bad Düben for the time frame 1961 - 2003. Two PWF bounds are given: i) without dyke breaching and ii) with breaching of dykes using maximum crest heights.*

breaching taking the maximum dyke crest height. The area between these two thresholds provides an uncertainty range and the region in which the flood frequency distribution should lie for very extreme floods. For discharges with a return period of up to 1000 years, any of the distributions may be valid for the flood frequency characterisation. However, for floods with return periods greater than 1000 years and on the basis of the short data series available from Bad Düben, it is evident that the distributions Generalised Logistics (GL), Generalised Extreme Value (GEV) and Log-Normal (LN3) overestimate the maximum flood discharges that may occur in the catchment area. The distributions which may better capture the possible worst flooding for the Mulde River are the Inverse Log-Normal (Logninv), the Gumbel and the Weibull distributions.

Conclusions

The probable worst flooding scenario for the Mulde River catchment could be successfully simulated with the modelling system. A large source of uncertainty is found in the data for dyke crest height. Simulating floods without dyke breaches and with dyke breaches using maximum crest heights provides an upper flood limit and a range in which the PWF discharge may lie.

References

Apel, H., Thieken, A.H., Merz, B. and Blöschl, G., 2004. Flood risk assessment and associated uncertainty *Natural Hazards Earth System Sci*., 4, 295–308.

Fleischbein, K., Lindenschmidt, K.-E. and Merz, B., 2006. Modelling the runoff response in the Mulde catchment. *Adv. Geosci*., **9**, 79–84, http://www.adv-geosci.net/9/79/2006/adgeo-9-79-2006.pdf

Harlin, J. and Kung, C.-S., 1992. Parameter uncertainty and simulation of design floods in Sweden. *J. Hydrol.*,**137**, 209–230.

Kleeberg, H.-B. and Schumann, A., 2001. Ableitung von Bemessungsabflüssen kleiner Überschreitungswahrscheinlichkeiten. *Wasserwirtschaft* **91**, 90–94.

Krause, P., 2001. Das hydrologische Modellsystem J2000 – Beschreibung und Anwendung in großen Flußgebieten, Schriften des Forschungszentrums Jülich, Reihe Umwelt/Environment, Band 29.

Macdonald, N., Black, A.R., Werritty, A. and McEwen, L.J., 2006. Historical and pooled flood frequency analysis for the River Tay at Perth, Scotland. *Area* **38**, 34–46

Merz, B., 1996. Modellierung des Niederschlag-Abfluß-Vorgangs in kleinen Einzugsgebieten unter Berücksichtigung der natürlichen Variabilität. Dissertation, Mitteilungen des Instituts für Hydrologie und Wasserwirtschaft, Universität Karlsruhe, 56, 215p.

Michalek, D., Drastig, K., Vorogushyn, S., Petrow, T. and Lindenschmidt, K.-E. (2007) Modelling the “probable worst flood” in the Mulde River catchment. 8. Forum DKKV/CEDIM: Disaster Reduction in Climate Change, 15–16. October 2007, Karlsruhe University.

Michalek, D., Drastig, K., Vorogushyn, S., Petrow, T. and Lindenschmidt, K.-E., (submitted). Flood frequency analyses with consideration of dyke breaches and a worst case event. *Korrespondenz Wasser*.

Petrow, T., Merz, B., Lindenschmidt, K.-E. and Thieken, A.H., 2007. Aspects of seasonality and flood generating circulation patterns in a mountainous catchment in south-eastern Germany. *Hydrol. Earth Syst. Sci*. **4**, 1455–1468, http://www.hydrol-earth-syst-sci.net/11/1455/2007/hess-11-1455-2007.pdf

Thorndycraft, V.R., Benito, G., Barriendos, M. and Llasat, M.C. (eds.), 2002. Palaeofloods, historical data and climate variability: *Applications in Flood Risk Assessment*. CSIC - Centro de Ciencias Medioambientales. ISBN-84-921958-2-7.

Vorogushyn, S., Apel, H., Lindenschmidt, K.-E. and Merz, B., 2007. Coupling 1D hydrodynamic, dike beach and inundation models for large-scale flood risk assessment along the Elbe River. *Proc. 7th Int.Conf. on Hydroinformatics* HIC 2006, Nice, France, 4– 8. September 2006. Research Publishing Services, ISBN: 81-903170-2-4. 481–488.