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Flood Safety versus Remaining Risks - Options and Limitations of Probabilistic Concepts in Flood Management

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Abstract Over decades, the planning of flood management was based on a safety-oriented approach. A design flood was estimated by probabilistic means to specify the limit up to which a flood should be controlled completely by technical measures. A case of failure was expected only in such cases where the design flood is overtopped. As design floods were specified by very small probabilities, the risk of a flood beyond the design flood was seen as negligible. Devastating flood events all over Europe raised the public awareness of remaining flood risks in the last two decades. Risk management became a political task in the EU. According to the European Flood Directive geographical areas, which could be flooded "with a low probability or under extreme event scenarios", have to be specified. The combination of "low probability" and "extreme event scenarios" demonstrates the problem of modern flood management. The existing probabilistic tools are not sufficient to specify the risks of failures, which result from critical combinations of multiple characteristics of hydrological loads. Scenarios are one option to specify them, but their probabilities stay unknown. Multivariate statistics could offer a way to fill this gap, but some problems of their practical application are still unresolved.

Keywords Flood risk · Design floods · Probabilities · Copulas

1 Introduction

In 1991 Vujica Yevjevich identified several tendencies, which were directed towards the development of particular new subdisciplines of hydrology (Yevjevich 1991). Among them he mentioned the hydrology of extremes, "which is intended to carry out indepth

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investigations of hydrologic extremes, particularly of floods and droughts, much beyond the classical hydrologic approaches, in order to help the complex solutions of various mixes of measures intended for the mitigation of impacts of extremes on human societies." There is no doubt that this tendency became a trend in the last 30 years. How far can we extrapolate it? To answer this question some problems of risk management (or impact mitigations) will be discussed here. Let's start with the status. Between 1980 and 2015, hydrological events (floods and mass movements) summed up to 39% of all relevant natural loss events (Munich Re 2016). Hydrological events caused 23% (928 billion US$) of overall losses and 14% of the 1.4 mil fatalities. The scientific community agrees that the risk of natural disasters is the product of the probability of a hazard and its adverse consequences. These consequences depend on the exposure, the amount of values present in the affected area, as well as on their vulnerability (loss susceptibility) (Merz et al. 2010). With the economic development, the exposure of values in flood plains is increasing in many parts of the world, but also the intensity and frequency of floods seem to increase in the last decades at least in some parts of the world. The reduction of flood risk is a current task to ensure the further social and economic development in many countries. We have to consider that flood risk is highly variable in time as flooding systems are continuously changing because of natural and socioeconomic processes, but also as the result of activities, which are intended to reduce flood risk (Hall et al. 2003b). The adaptation to these changes and the structuring of appropriated strategies to reduce flood risk in future under consideration of the uncertainties is a challenging task in water management.

The traditional approach to flood engineering was focused on the hazard. Technical measures were planned to prevent flooding. For this purpose, the planning was based on a design flood event. The return period of this design flood (precisely: the return period of the flood peak) was a substitute for the level of flood safety, which has to be ensured by the planned technical measures. It was specified by probabilistic criteria with two basic assumptions. The first one is that the design flood should define the limit up to which a flood has to be controlled completely by technical measures and the second one that a failure of the system has to be expected only in such cases where the design flood is overtopped. In some cases, both aspects were separated into two design cases. The German standard for dams (DIN 2004) specifies for example one design flood, which has to be controlled by a reservoir without any damaging of the technical structure, and another one which has to be used to demonstrate the security of the structure. In this second case, damages to components may be accepted as long as the load-bearing capacity of the structure is preserved (Sieber 2000). With the aim to demonstrate a high safety, often design floods with very small probabilities were used. In the case of German reservoirs e.g. exceedance probabilities of the flood peaks of 10^{-3} (case 1) or 10^{-4} (case 2) are demanded. As a result, the risk of a flood beyond the design flood seems to be very small and neglectable. This safety orientation resulted in the need to estimate flood peaks with very low exceedance probabilities and even the need to specify the maximum precipitation (PMP) and probable maximum flood (PMF). Yevjevich discussed this problem as follows "Furthermore, the request by the public to decrease risks will force specialists in the hydrology of extremes to undertake a new round of research on how to more accurately estimate floods of very small probabilities of exceedence (say, once in ten thousand to once in ten million years)" (Yevjevich 1991).

With the increasing flood risk awareness, the dilemma of this safety-oriented concept of technical measures (Costa 1978) became more evident. With increasing expenditures for flood control, the losses from flooding continued to rise. New "protected" flood plains were used more intensively, but at the same time the limitations of flood defense became evident by unexpected extra-ordinary events or unconsidered mechanisms of failures. The general focus on flood defense and the assumption of an almost complete flood control was replaced by the acceptance that flood risk can be mitigated only up to a certain level by technical measures. A transition in flood policy gave emphasis upon reducing harmful consequences of flooding. An example for such an flood risk based approach is given by Kellens et al. (2013).

There are two main challenges for flood engineering resulting from this development:

a. The focus shifts from the safety of flood defense to the remaining risk of failures of technical systems.
b. Single measures have to be evaluated within a basin-wide context of risk assessments at multiple locations. This demands a consideration of their spatial regions of influence as well as of the affected regions in the case of failure.

After a short characterization of the concept of integrated flood risk management, the options and limitations of multivariate probabilistic concepts in flood risk management are discussed. An example of a case study is used for this purpose.

2 The Hydrological Challenge of Flood Risk Management

Flood risk management aims today to reduce the likelihood of flooding as well as its harmful consequences. For this purpose, flood risk management has to address a wider range of hydrological events, including those, which are exceeding design standards. Also processes, which may cause flooding if the event stays below these design standards, have to be considered. This may be due to expected but also unexpected failure modes or other flooding sources (Merz et al. 2010). According to the European Flood Directive (EFD) flood risk management has to consider the eventuality of flood damages in geographical areas which could be flooded “with a low probability or under extreme event scenarios” (European Commission 2007). According to this formulation, the remaining risk, including the opportunity of failures of technical flood protection, has to be considered in European flood risk management plans.

An integrated flood risk management has to consider the interrelationships between all risk management measures, their costs and effectiveness (Hall et al. 2003b). Flood risk management has to be effective but also efficient. The effectiveness of planned measures in their potential to reduce risk can be assessed with specific design floods. In the planning process, which is specified by the EFD (European Commission 2007), a prioritisation of measures aiming to achieve the appropriate objectives of flood risk management is foreseen. Such a prioritisation demands a risk-informed decision-making, which has to be based on such aspects as costs and benefits. Cost-benefit analyses in risk management demand that the amount invested in risk reduction is in proportion to the magnitude of the risk and the cost-effectiveness with which that risk may be reduced (Merz et al. 2010). To estimate and to compare the risk reduction from technical measures, the remaining risk of failures, which may result from the hydrological risk of an extreme flood, but also from operational and technical risks, has to be accounted. The overall return on investments in flood protection demands a specification of their performance over the full period of live under consideration of the stochastic character of floods and the permanent risk of failures.

Performance-based planning of flood defense structures requires a representation of their fragility. For this purpose fragility curves can be used to quantify the relationship between the loading on a structure and the conditional probability of failure given that loading (Simm et al. 2009). In difference to the safety-oriented approach of flood design, which is based on a proof of functional safety, we have to look beyond design flood events to incorporate the consequences of failures of technical structures into decision-making. As many different modes of failures exists, we are challenged to specify a large variety of hydrological loads, which could be critical for structures of technical flood protection. For this purpose the probabilistic concept of design floods, which are specified by the exceedance probabilities of their flood peaks, has to be extended. Flood risk management depends on a balance between protection and preparedness. If the opportunities of technical flood protection are overassessed, the need for preparedness will be underestimated.

A crucial problem to apply probabilistic concepts in flood risk management results from the need for an integrated system approach. Flood risk management is aimed at managing whole flooding systems by their catchments in an integrated way that accounts for all of the potential interventions that may alter flood risk (Sayers et al. 2002). In this way, the spatial scale of planning has to be extended from local sites where flood defense has to be improved, to river basins districts or river basins as a whole where flood risk has to be reduced. In safety-oriented flood planning, technical flood protection measures were designed to protect one or multiple flood-endangered objects. This could be a settlement, a part of the infrastructure, an industrial plant or (more general) a floodplain. Integrated flood risk reduction demands now a basin-wide impact assessment of all these measures. This is a precondition to assess and weight measures among each other according to their effectiveness. At this extended spatial scale, their effects on local, regional and supra-regional flood risks may differ and often depend on event-specific interactions between tributaries and the alterations of floods by other interventions in the flood regime, which may differ in their impacts between events. Analyses of the downstream impacts of single flood protection measures was a basic component of safety oriented flood design before. New is the need for a systemic approach to assess overlaying impacts of measures with their cumulative contribution to risk reduction. In this way an integrated approach demands a consideration of spatial interactions, an assessment of the performance of single components of technical flood protection and of the system as whole as well as an assessment of the risk of single and multiple failures of its components.

With regard to probabilistic assessments, there exists a gap between the classical flood design, specifying the functional reliability of flood protection structures under assumption of specified design flood events, which are characterized by return periods, and the need to consider the limits of these structures and the remaining risks. This remaining risk consists of two components: the risk, which is related with unexpected failure modes (an epistemic uncertainty) and the risk, which results from hydrological loads, which are overtopping the bearing capacities of these structures. Statistical models to handle them as aleatoric uncertainties can specify these hydrological loads. The risk of failures of technical structures depends on their fragility. If several failure mechanisms exist for one structure, different fragility curves have to be considered, which depend normally on different loads. As the characteristics of these loads are interrelated, a multivariate statistical approach is needed to specify their interdependencies. To specify e.g. the risk of a dyke failure, breach and overtopping has to be considered. Breaching and overtopping are dependent failure mechanisms as overtopping is very often the initiating mechanisms of a breach. Depending on the duration of high water levels, piping and slope failures may also cause breaching without overtopping (Bachmann et al. 2013). In this way, the flood peak and the highest water level related to it are essential to specify the risk of a dyke failure by overtopping, but are not sufficient to characterize the total risk of failure. The duration of an impounding, which results in critical water levels with regard to piping and slope failures is also very important. It is related with the flood peak by the shape of the hydrograph and the flood volume.

As mentioned above, flood risk management requires a basin-wide approach. The river basin network and the spatial distribution of rainfall cause uneven spatial distributions of hydrological loads. The resulting overlay of flood waves and the event-specific spatial impact of flood defense structures as well as the spatial distributed consequences of their failures modify these hydrological conditions. The demand for a basin-wide flood risk management requires new concepts to consider spatial interactions of components of flood protection systems and to specify the temporal synchronicity of spatial distributed hydrological loads. This is relevant for the optimal allocation of storage capacities, but also for an assessment of the remaining risk resulting from unusual spatial distributions of rainfall and/or of failures of local flood protection systems (Apel et al. 2009). In this way flood risk management is a much more complex task as the specification of a design flood and requires new probabilistic tools and methodologies.

The most of the questions raised above could be answered in a deterministic way by a utilization of flood scenarios. However, probabilistic methods form the base for current flood engineering and also the definition of risk includes the need for a specification of probabilities. Not least, regulations how to assess and manage flood risk, e.g. the EFD, are based on a probabilistic characterisation of hydrological loads. In the EFD risk assessments are demanded for “low, medium (return periods ≥ 100years) and high” probabilities. So we are faced with the problem how to specify flood probabilities under such complex flood conditions, how to determine the remaining risk of failures of flood defense structures and how to consider the spatial interactions of tributaries, sub-basins and flood defense systems within a river basin with an appropriated probabilistic framework. The probability of failure of a flood defense system can be estimated using the methods of structural reliability analysis (Hall et al. 2003a). However, application of these methods requires probability distributions for the hydraulic loads, which are interrelated with hydrological loads (highest water level, duration of water levels above certain thresholds). The existing probabilistic tools are not sufficient to specify the risks of failures, which results from critical combinations of multiple characteristics of hydrological loads if they are focused on the flood peak discharge only. Flood scenarios are one option to overcome the problem of multi-dimensionality, but their probabilistic characterisation is very difficult and requires new statistical tools.

3 Univariate Extreme Value Statistics in Flood Risk Management

Extreme value statistics is one of the main uncertainties in flood risk assessments (Apel et al. 2008; Apel et al. 2004). Probability Distribution Functions (PDF) are the medium of choice to specify the aleatory uncertainty resulting from the randomness of a phenomenon. With regard to the uncertainties of an appropriated selection of a distribution function e.g. of annual maximum discharge and the sampling uncertainty of the discharge data, its application is related with many epistemic uncertainties, which are caused by a lack of our knowledge. The example of Fig. 1 demonstrates the general problems. The courses of the different PDF are very similar in the reach of low return periods, but diverge strongly in their upper tails. The selection of a “best” PDF is difficult. Often the need for longer time series is reasoned by this uncertainty. However, also if we consider historic floods, the limitations of the extrapolation of PDF become evident. In the example in Fig. 1, a flood peak of 1050 m^3/s was not exceeded (as far as we know) within the last 500 years (since the year 1432). This may be is caused by specific hydraulic conditions upstream, but also by the false assumption that the observations are homogeneous, i.e. subject to a common set of forces. Cunnane underlined the need for a physical justification for upper tail behavior of PDF-estimations with regard to outliers, log and other data transformations or arbitrary use of mixtures of distributions (Cunnane 2009). Upper tails are still a crucial problem in flood statistics, which is aggravated by the uncertain impacts of climate change on extremes. The eventuality of nonstationarity implies that our already uncertain knowledge is less valuable and more difficult to extrapolate into the future than for the stationary case. Milly et al. formulized this challenge in research as follows: “We need to find ways to identify nonstationary probabilistic models of relevant environmental variables” (Milly et al. 2008). However, to find such models we need additional information to attribute changes to the atmospheric, catchment and river system drivers as well as methodologies to specify their impacts (Hall et al. 2014; Viglione et al. 2016). To apply such nonstationary models in flood risk management, we have to imply that the time-varying model structure holds true for the future life period of the planned technical measures. If a nonstationary model is fitted by inductive inference only, the model structure introduces an additional source of uncertainty (Serinaldi and Kilsby 2015). We have to consider that flood populations, from which our samples arise, are quite variable in nature having high values of coefficient of variation and skewness. Cunnane noticed in 1987: “it is inevitable that some samples from such populations will contain either low or high outliers, which in turn effect quantile estimates in a manner which may not always be plausible” (Cunnane 1987). If an extreme flood event occurs once it can change the results of flood statistical analyses more than the most

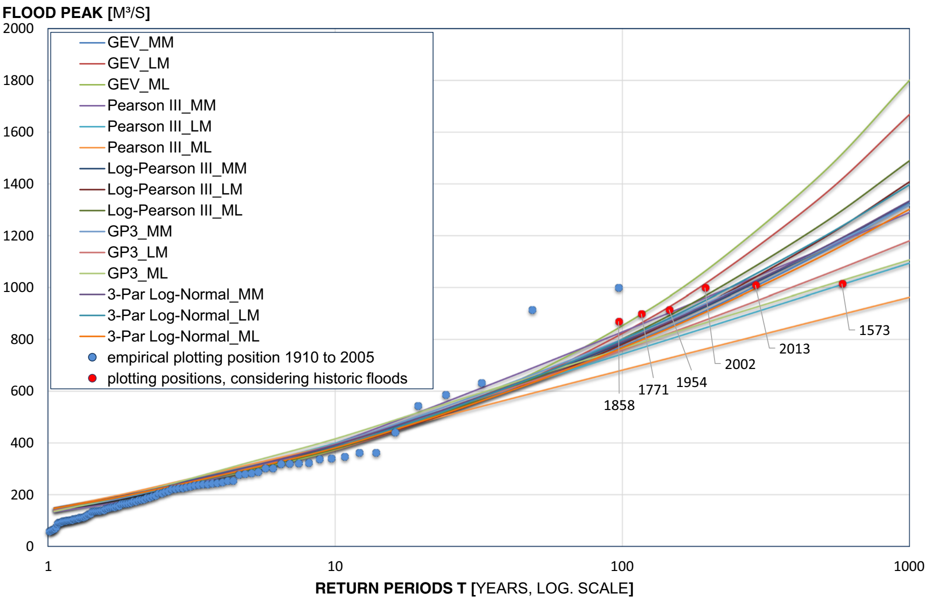

Fig. 1 Distribution functions for the yearly flood peaks at the gauge Wechselburg/Zwickauer Mulde in Germany for the time period 1910 to 2005 with five historic floods since 1432

expectations about climate change impacts. There are some attempts to increase the robustness of flood statistics (Fischer and Schumann 2015), but the problem, how to adjust the statistical results from short series in such a way that the outcome would be similar if the observation period would be doubled or tripled is still unresolved.

4 Multivariate Statistics in Flood Risk Management

As described above, the complex task of flood risk management demands considerations of complex failure modes for flood defense structures as well as of spatial and temporal interdependencies of flood events at multiple sites. A probabilistic characterization of flood hazards at the river basin scale requires a consideration of many multivariate problems:

- The impact of technical flood protection and their risk of failures demands a specification of multivariate probabilities to specify a critical flood event at one site by several interrelated flood characteristics (e.g. peak and volume),
- The spatial extent and the interrelationships between flood sites depend on the spatial and temporal distribution of rainfall in interaction with the basin characteristics (Woods and Sivapalan 1999). Here, a multivariate probabilistic approach is essential to characterize the cases of coincidences of extreme events at multiple sites within a river basin and the impact of flood defense measures in a basin-wide context (Schulte and Schumann 2015).

In the last years, Copula- applications became very popular to set up multivariate statistical models.

The hydrological risk in the univariate case is defined by the probability that the random variable X (generally the flood peak) exceeds a critical design value x. Thus critical situations are characterized by $X > x$. In the multivariate case, where we have to consider several variables at the same time, the critical region is multi-dimensional. These variables often show a statistical correlation. For example, the volume of a flood wave normally accumulates with a rising flood peak. In addition, flood peaks of tributaries in a basin are normally statistical interrelated according to the spatial extent of flood events. In the last two decades copulas have becoming more common in hydrology (Salvadori and De Michele 2004; Salvadori and De Michele 2007; Klein et al. 2010) to consider such multivariate dependencies between random variables in critical flood scenarios (Favre et al. 2004; Zhang and Singh 2006). Copulas allow a flexible modelling of dependencies between random variables and the utilisation of different marginal distribution functions to build a probabilistic multivariate model. The method of copulas is based on the theorem of Sklar (1959). It expresses the connection between a copula-function C and the univariate cumulative distribution functions (CDF) of correlated random variables $X_1,\ldots,X_d$, which can be described separately by their marginal cumulative distribution functions $F_1,\ldots,F_d$:

$$F(x_1,\ldots,x_d) = C[F_1(x_1),\ldots,F_d(x_d)] = P(X_1 \le x_1,\ldots,X_d \le x_d) \quad (1)$$

An introduction to Copulas is given by Nelsen (Nelsen 2006). There are several types of Copulas available. One main application of copulas is to support the planning of flood retention, considering the dependencies between peak and volume (De Michele et al. 2005;

Shiau et al. 2006; Klein et al. 2010). Most common in hydrology is the application of Archimedean copulas (Nelsen 2005).

A crucial problem of multivariate statistics consists in the estimation of the probability of a certain event, which is defined by a combination of dependent random variables. Such a hydrological event cannot not be described sufficiently by a univariate frequency analysis of one variable (mostly of the flood peak). At the other side a multivariate statistical approach makes it difficult to continue with the classical concept of return periods, which was introduced more than 100 years ago (Volpi et al. 2015). A return period of a given event is usually defined as the average time elapsing between two successive realizations of the event of interest. In univariate flood design the "event" is specified only by the exceedance of the discharge value of the flood peak. Its estimation is based on the natural ordering in univariate time series of flood peaks. Other associated characteristics (e.g. volumes or shape parameters of the hydrograph) are assumed as boundary conditions under consideration of previous events and/or regional hydrological knowledge. Going from univariate to multivariate cases we are faced with the lack of a natural ordering for problems of dimension $d \geq 2$. Several options to estimate design events in the multivariate case are proposed. Gräler et al. (2013) proposed an approach, where a bivariate distribution is conditioned for the quantile of interest for a leading variable. A conditioned distribution is used to obtain the other quantile. This approach would result in two different probabilities. A multivariate copula-based framework to use multivariate statistics to estimate hazard scenarios and failure probabilities was presented by (Salvadori et al. 2016). It differentiates between scenarios based on "OR" and "AND" cases, the Kendall scenario and the Survival Kendall Scenario. In the OR case it is sufficient that one of the variables $X_{1...d}$ exceeds the corresponding threshold x_i. In the AND case all variables $X_{1...d}$ exceed their thresholds $x_{1...d}$. The Kendall return period (Salvadori et al. 2011) is based on the Kendall Distribution Function and separates safe from dangerous events by the distribution of the copula's mass below its level curve. The critical layer to separate both event types is unbounded such that one of the margins might tend to infinity. To overcome this limitation, the Survival Kendall return period was introduced (Salvadori et al. 2013). It is based on the survival copula, which combines the marginal survival distribution functions and the most reliable separation into safe and dangerous events. Common of all these approaches is the option to differentiate between safe and dangerous regions in the multi-dimensional space of events by marginal CDFs or multivariate probabilities. However, there exist numerous events with the same multivariate probability. In this way, the flood design is faced with a problem of multi-dimensionality, where one probability is insufficient to characterize the many possible outcomes of events. The main problem of approaches to specify multivariate return periods consists in the selection of a single design flood event, which is still required for technical flood measures. As mentioned above a practical applicable tool to handle this problem consists in the specification of scenarios (Salvadori et al. 2016). The selection and acceptance of such scenarios by decision makers involve subjective components. In one publication Cunnane quoted Fiering, who wrote: "The statistical significance of one distribution or another, the degree of resolution of the tail of one distribution or another, the plotting position or the return period associated with a particular event represent operationally meaningless questions unless they are framed within the context of making decisions." (Cunnane 1987). Such a framing demands in our case a communication of problems to handle multiple random variables as well as of the need to accept a decision space in risk assessments, which differs from safety oriented flood design. How this could be done is demonstrated with the following case study (Klein et al. 2011).

5 A Case Study for a Combination of Flood Design with Flood Risk Assessments

The following example of a flood control system for the Unstrut River in Germany demonstrates some of the problems, which are discussed above. The system consists of a river basin with a catchment area of 6343 km^2, which is situated in Mid-Eastern Germany with two large flood control reservoirs. The reservoir Kelbra has a catchment area of 664 km^2 and a flood control storage of 35.6 10^6 m^3 and the flood detention reservoir Straussfurt a catchment area of 2044 km^2 and a flood control storage of 18.6 10^6 m^3. Both reservoirs are located parallel to another at the two main tributaries. A large polder system with a total storage volume of approximately 50 10^6 m^3 is located downstream of the point of confluence of both tributaries (Fig. 2).

The system was analysed to specify the potential to reduce the flood peak at the gauge Wangen, which is situated at the boundary of the German federal state of Thuringia with 5 different combinations of technical measures to improve flood detention in the polder system.

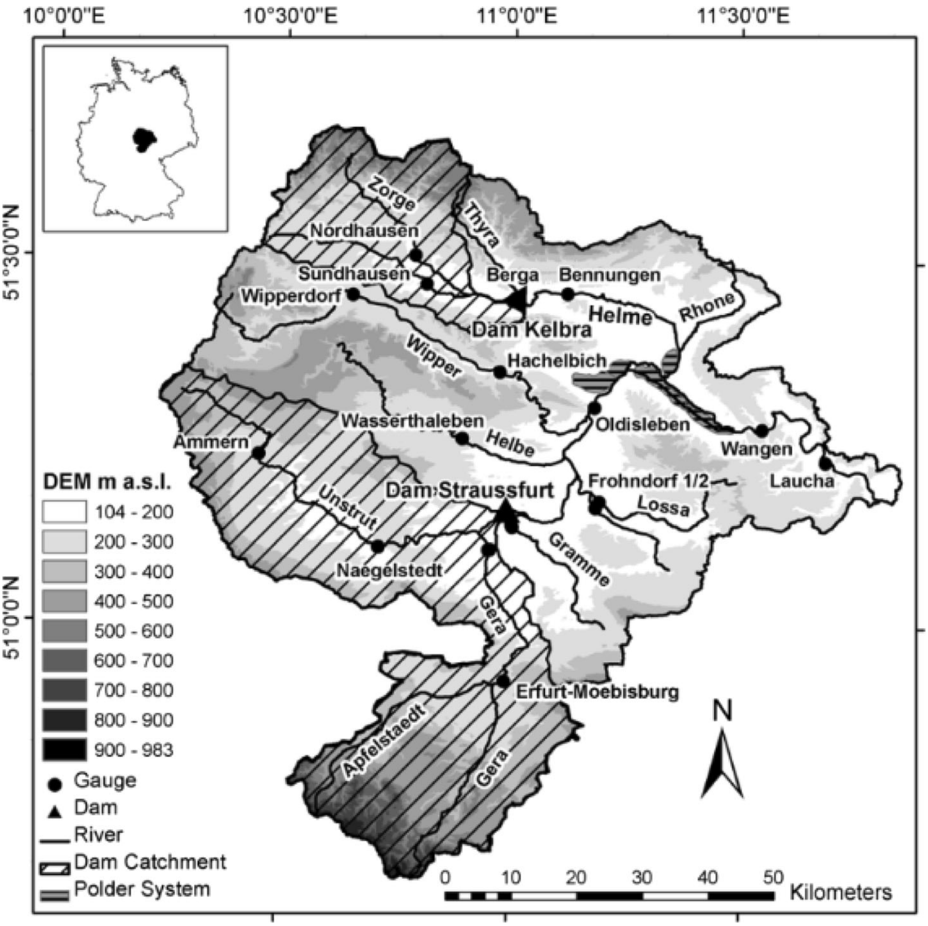

Fig. 2 Map of the Unstrut River Basin with a flood control system, consisting of two reservoirs and a polder (Klein et al. 2011)

The water management authority was interested in the reductions of flood peaks with different return periods. As flood conditions were modified by flood retention facilities, which were built within the last 50 years, the observed data could not be used to answer this question. An option to consider such non-stationarity of the boundary conditions consist in a coupling of stochastic rainfall generators with hydrological models within a semi-deterministic Monte-Carlo-Simulation approach (Charalambous et al. 2013). The hydrological and/or hydraulic model can consider the changes of watersheds in impact assessments. A long-term daily discharge time series of 10,000 years was generated by coupling a stochastic spatially distributed daily rainfall generator (Hundecha et al. 2009) with a hydrological rainfall-runoff model based on the concept of the widely used Swedish hydrological model HBV-96 (Lindström et al. 1997). A representative sample flood events for six different return periods at the gauge Straussfurt (T = 25, 50, 100, 200, 500, 1000 years) was selected. This selection was supported by cluster analyses of observed events to determine typical hydrograph shapes and volumes. In total five different hydrological scenarios were selected for each return period at the reference gauge Straussfurt, which encompass various spatial and temporal distributions of precipitation. The limitation on 30 events was necessary to simulate hydraulics of inundated flood plains by a two-dimensional model.

For flood storages such as reservoirs and polders, it is important to consider the flood volume besides the flood peak to assess the performance of flood detention. Corresponding values of annual flood peaks and flood volumes from the 10,000 years of simulated data were used to parameterise two bivariate Copula models for peak- volume relationships of flood events at the inflow gauges of both reservoirs. These statistical models were used to simulate new time series of corresponding characteristics and to specify the bivariate probabilities of the selected 30 flood scenarios at both sites. One example is given in Fig. 3. It shows the joint return periods $T^{\vee}_{X,Y}$ (exceeding x or y) and $T^{\wedge}_{X,Y}$ (exceeding x and y) of corresponding flood peaks X and flood volumes Y at the reservoir site Straussfurt. The arrow demonstrates the range of the flood volumes for a selected flood peak. Here the flood peak has a return period of 100 years, but the return periods of corresponding volumes varies from less than 50 up to 2000 years.

As the catchment size of both reservoirs differs as well as their flood storages, the performance of the flood control system is significantly affected by the spatial rainfall

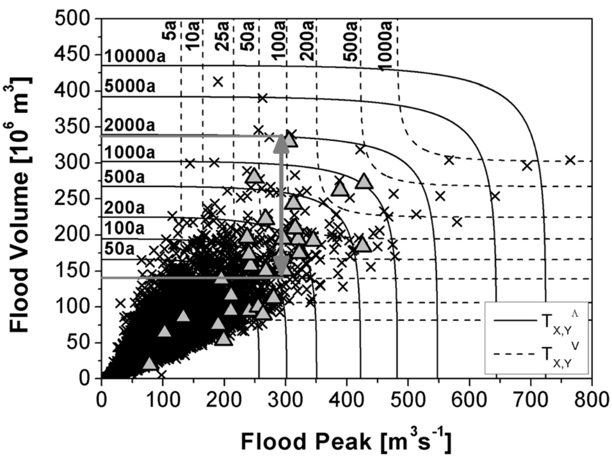

Fig. 3 Joint return periods $T^{\wedge}$X,Y (exceeding x or y) and $T^{\vee}$ X,Y (exceeding x and y) of flood peaks and corresponding flood volumes at the reservoir Straussfurt, the annual events from the simulated time series (black x) and the selected hydrological scenarios (grey triangles) (Klein et al. 2011)

distribution. If the flood-inducing rain is concentrated on the watersheds in the Northern or Southern parts of the basin, the runoff can be controlled by the reservoirs. Both reservoirs differ in their relationships between catchment area and storage capacity. If the main part of the rainfall falls in the central part of the river basin, the effect of both reservoirs would be limited. Bivariate probabilities of synchronous flood peaks at the inflow gauges of the Kelbra and the Straussfurt reservoirs were applied to consider these effects. These bivariate probabilities of corresponding flood peaks at the two inflow gauges were also estimated from a Copula model (Fig. 4) to consider coincidences of flood events in both tributaries (Klein et al. 2010). In 73% of the simulated 10.000 years, the annual floods happened synchronously at both sites. Fig. 4 shows the joint return periods of these events and of the 30 flood scenarios. The arrow again demonstrates the range of differences between univariate probabilities of corresponding flood peaks. A flood with a return period of the peak of 300 years at the gauge Straussfurt can happen at the same time with floods, which have return periods between 60 and 650 years at the gauge Kelbra. By pairwise copula statistics each of the 30 flood events was characterised by joint probabilities of the flood peaks and corresponding volumes at the inflow gauges of the reservoirs Straussfurt and Kelbra as well as by probabilities of corresponding flood peaks at both reservoir sites. The flood scenarios were used to simulate the flood detention within the polder system with different structural modifications of this system and to estimate the resulting reduction of flood peaks at the outlet of the basin.

The results were unexpected by the decision makers. By application of five flood scenarios per return period (which was defined at the reference gauge Straussfurt) it was demonstrated that the flood conditions differ so much that an assessment of the performance of the flood retention system depends strongly on the boundary conditions. In Fig. 5 the estimated reductions of the water level at the outlet gauge in Wangen are shown for three different states of the polder system. In general, the average reductions of the water level become smaller with increasing return periods peaks at the gauge Straussfurt. It becomes obvious that the reconstructed polder system could have a high performance, even for floods with a very large return period of 1000 years (defined by the peak at the reference gauge Straussfurt under very favourable conditions), where the two reservoirs would reduce the flood peaks of both tributaries significantly. On the other hand, the system could fail even for floods with return periods of 25 or 50 years under unfortunate conditions (high volumes of the floods). The

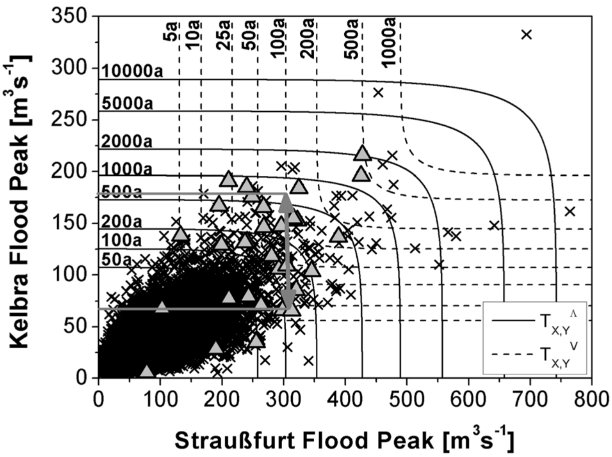

Fig. 4 Joint return periods $T^{\vee}_{X,Y}$ (exceeding x or y) and $T^{\wedge}_{X,Y}$ (exceeding x and y) of simulated corresponding flood peaks at the two reservoir sites (black crosses) and of the selected hydrological scenarios (grey triangles)

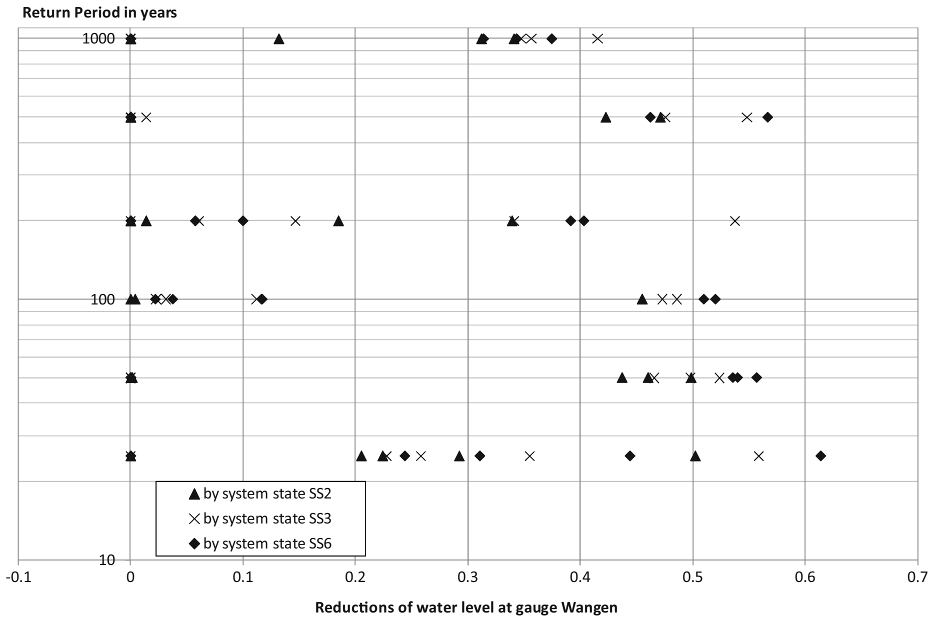

Fig. 5 Reductions of the flood peak at the basin outlet by 30 flood scenarios for 3 states of the polder system (Schumann and Nijssen 2011)

problem of this differentiation of critical and non-critical events consists in complexity of the flood conditions, which result in one of both types. The following probabilities were provided for each flood scenario:

- Return periods of the flood peaks at the inlets of the two reservoirs,
- Return periods for the cases AND and OR and the Kendall- return periods to characterise flood scenarios separately by their peak-volume- relationships for each one of both reservoirs,
- AND and OR return periods and the Kendall-return period of synchronous flood peaks at both reservoir sites.

The relevance of these return periods depends on the component of the system, which is of interest. The performance of each of the two reservoirs for a flood with a certain return period of its peak depends on the flood volume. For low return periods of the peak, the flood volumes are less critical than for high return periods. Here the joint return period of the case AND are of interest. The coincidence of flood peaks in the two main tributaries and the risk of overlaying flood waves is highly relevant for the hydrological load of the polder system. Again the AND case seems to be most interesting, however a critical situation can be also specified by the OR case, if it would be sufficient that a very large flood originates from one of both sub-basins.

In this case study, the flood scenarios were specified in a rather pragmatic way with a qualitative indicator, by their plausibility. If all the peaks, volumes and spatial distribution patterns have nearly the same probability, the event seems to more plausible than if their probabilities differ very much. The degree of plausibility was specified by triangular fuzzy numbers to characterise how representative each flood scenario is. These fuzzy numbers were used to specify the uncertainty of flood damages, which were estimated for each flood scenario under assumption of one of the five planned measures to modify the polder system. A Decision Support System, using a Fuzzy-AHP (Analytical Hierarchic Programming) approach (Srdjevic and Medeiros 2008) where these fuzzified damages could be integrated, supported the decision process.

6 Summary, Conclusions

Univariate analyses are fine if only one variable is significant in the design process (Salvadori and De Michele 2004). In the "context of making decisions" (to quote Fiering) this is still the case. The EFD e.g. does not differ between univariate and multivariate cases. It demands management plans for scenarios of floods with low, medium and high probabilities. But if we intend to implement the concept of integrated flood risk management, we have to specify scenarios, which are representative for conditions with a high potential risk. Univariate analyses will be not sufficient if such risks result from a coincidence of unfavourable conditions, which cannot be specified by the probability of a flood peak at one reference gauge. Such critical scenarios could result from boundary conditions, which limit the performance of flood defence considerably (e.g. a breach of a dyke, which would result in unusable evacuation routes). A probabilistic framework to specify probabilities of more or less critical combinations of many different boundary conditions, which are affecting the flood probabilities at many different locations within a river basin cannot be specified in technical regulations. For risk management is it essential to specify events, which has to be avoided in any circumstances and to assess the range of events, we should consider to improve our preparedness. Multivariate statistical analyses are very useful in this context as they increase the understanding of uncertainties and the acceptance of "known unknowns". Multivariate probabilities can be used to compare scenarios in the sense of Multiple-Criteria Decision-Making. They are useful to consider different components of risks and to allocate measures of flood risk management to hotspots.

According to a survey carried out by the German Insurance Association (GDV), the insurers paid a total of 1.8 billion euros for about 140,000 insured losses for flood damages in Germany in 2013. Surprisingly 85% of these damage occurred far outside of risk zones, which were assumed particularly vulnerable. This means that the majority of all damages occurred in areas, which should be affected only by floods with return periods of 200 years or more rarely (GDV 2014). This example demonstrates the need for a flood management planning, which is not based on the safety-oriented design aspects (however which will be still valid in future for technical planning of single measures) but on an awareness of "known unknowns". Here hazard scenarios in combination with failure probabilities can be applied to cover the wide range of possible situations. The decision space of flood management can be explored by these scenarios and multivariate statistics could be a guide to do this.

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