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Significance of "high probability/low damage" versus "low probability/high damage" flood events

B. Merz[1], **F. Elmer**[1], **and A. H. Thieken**[2]

[1]Deutsches GeoForschungsZentrum GFZ, Telegrafenberg, 14473 Potsdam, Germany
[2]alpS – Centre for Natural Hazard and Risk Management and University of Innsbruck, Grabenweg 3, 6020 Innsbruck, Austria

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Abstract. The need for an efficient use of limited resources fosters the application of risk-oriented design in flood mitigation. Flood defence measures reduce future damage. Traditionally, this benefit is quantified via the expected annual damage. We analyse the contribution of "high probability/low damage" floods versus the contribution of "low probability/high damage" events to the expected annual damage. For three case studies, i.e. actual flood situations in flood-prone communities in Germany, it is shown that the expected annual damage is dominated by "high probability/low damage" events. Extreme events play a minor role, even though they cause high damage. Using typical values for flood frequency behaviour, flood plain morphology, distribution of assets and vulnerability, it is shown that this also holds for the general case of river floods in Germany. This result is compared to the significance of extreme events in the public perception. "Low probability/high damage" events are more important in the societal view than it is expressed by the expected annual damage. We conclude that the expected annual damage should be used with care since it is not in agreement with societal priorities. Further, risk aversion functions that penalise events with disastrous consequences are introduced in the appraisal of risk mitigation options. It is shown that risk aversion may have substantial implications for decision-making. Different flood mitigation decisions are probable, when risk aversion is taken into account.

1 Introduction

Recently, increasing interest in risk-oriented flood design can be observed (e.g. Sayers et al., 2002; Dawson and Hall, 2004; Rose et al., 2007). In this context risk is understood as the combination of the probability of a particular event and of the impact that this event would cause if it occurred. Risk-based design strives to balance benefits and costs of the design in an explicit manner. In this context, benefits and costs have to be understood as broad terms encompassing not only monetary outcomes but any other effects such as ecological or social ones. An optimal flood defence system, chosen from multiple options, can be found by minimising the life-cycle costs, i.e. the expected costs during the lifetime of the system. These costs include failure costs which are related to the adverse effects of system failures. Hence, a risk-based approach compares the expected outcomes and costs of alternative courses of action, and the design of the flood defence is found via optimisation. On the contrary, a standard-based engineering approach limits itself to the probability of the flood, by imposing a certain flood return period that the flood defense has to withstand.

Risk-based flood design is frequently based on cost-benefit analyses. In Germany, for example, public investments in flood mitigation have to be supported by cost-benefit analysis. Flood defence schemes are aimed at reducing the flood damage that is expected during the lifetime of the scheme. Hence, the reduction of future damage, i.e. the flood damage avoided, is considered as principal benefit in cost-benefit analyses. The difference between the costs for the flood defence and the benefits of the defence scheme, i.e. the damage avoided, has to be maximised. Although benefits and costs should be understood in a general sense, risk-based flood design is usually limited to monetary effects. Intangible effects, such as recreational costs or benefits (e.g. Penning-Rowsell

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Correspondence to: B. Merz
(bmerz@gfz-potsdam.de)

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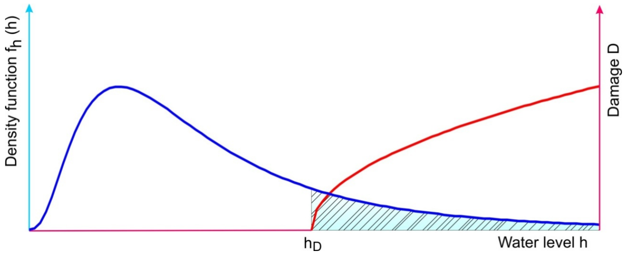

Fig. 1. Probability density function of the flood water level and damage function. The shaded area is the probability of a flood water level leading to damage.

and Green, 2000) or adverse health effects (e.g. Tapsell and Tunstall, 2001; Jonkman and Kelman, 2005), are frequently neglected.

In the majority of flood design cases, the annual damage expectation is used as risk indicator (e.g. Penning-Rowsell and Green, 2000; van Manem and Brinkhuis, 2003; Merz, 2006). Given the dominance of the expected annual damage (EAD) as risk indicator, it is interesting to investigate the implications of this use for flood defence decisions. As early as 1958, Eckstein criticised the concept of EAD. He pointed out that, whereas initiatives for structural flood defence measures are mainly triggered from public reaction to disastrous floods, the EAD-based design minimises the long-term, average damage (Eckstein, 1958). The concept of EAD assumes that decision makers and people-at-risk are risk-neutral, and that they strive to maximise economic efficiency. However, people tend to be risk-averse (e.g. Bohnenblust and Slovic, 1998). Risk aversion refers to the observation that events with the same damage expectation might be perceived very differently. People tend to dread events with large adverse consequences, even if their probability of occurrence is very small, and consequently their damage expectation is very small, too.

A few alternate approaches that are not only based on expectation have been proposed, but are seldom applied. The partitioned multiobjective risk method (PMRM; Asbeck and Haimes, 1984; Haimes, 1998) separates the probability axis into n regions, and the expected value is calculated for each region. The low-probability expectation is a measure for the average largest damage, given the events of an extreme nature (Karlsson and Haimes, 1988). By including the low-probability expectation as an objective, catastrophic events can explicitly be included in the decision problem. Further alternate methods, such as the mean-variance rule, are discussed by Mechler (2004).

Hergarten (2004) investigates the contribution of large and small events to EAD for different natural hazards under the assumption that the event size is power-law distributed. He concludes that EAD is mainly governed by the largest events for earthquakes, forest fires and rockfalls, while results are non-unique for landslides. This paper analyses this question for river floods. The relative contribution of extreme events (high probability/low damage) and frequent events (low probability/high damage) to EAD is quantified for three case studies and for the general case of riverine flooding in Germany (Sect. 2). Section 3 summarises research findings concerning risk perception and compares the results of Sect. 2 with these findings. Section 4 investigates the implications of integrating different risk preferences (risk neutral versus risk adverse) in risk-based flood design. For three communities, the risk reduction due to hypothetical flood defence measures is compared for the usual EAD approach with an approach that considers risk aversion. It is shown how the inclusion of risk aversion might influence the decision on flood protection measures.

2 Significance of "low probability/high damage" floods using the EAD concept as risk indicator

2.1 Damage expectation as risk indicator

Applying the EAD concept to the case of riverine floods yields:

$$RI = \int_{h_D}^{\infty} f_h(h)\, D(h)\, dh \tag{1}$$

The flood risk RI, i.e. the probability of a certain flood damage within a given time period, depends on the probability density function $f_h(h)$ of the flood water level h, and on the relation between h and the flood damage D. The lower integration limit is h_D, the threshold water level above which flood damage occurs. Figure 1 illustrates this relation. With increasing water levels, and above the damage threshold h_D, damage D is increasing and the probability density $f_h(h)$ is decreasing. According to this definition, risk has the same unit as the damage indicator, related to the time interval of $f_h(h)$. Traditionally, an annual time span and monetary damage are chosen, and the flood risk RI is given as annual flood damage (in Euro or any other currency).

In flood risk analysis damage estimates are frequently given for a few flood scenarios, to which certain return intervals and discharges are connected. These discrete scenarios are approximations of the continuous distribution function $f_h(h)$ of the annual flood water level h. In this case, Eq. (1) has to be replaced by:

$$RI = \sum_{j=1}^{m} \Delta P_j\, D_j \tag{2}$$

where D_j and ΔP_j are the average flood damage and the exceedance probability increment for the j-th interval, respectively, and m is the number of probability increments:

$$D_j = \frac{1}{2}\left(D\left(h_j\right) + D\left(h_{j+1}\right)\right) \tag{3}$$

$$\Delta P_j = P\left(h_j\right) - P\left(h_{j+1}\right) \tag{4}$$

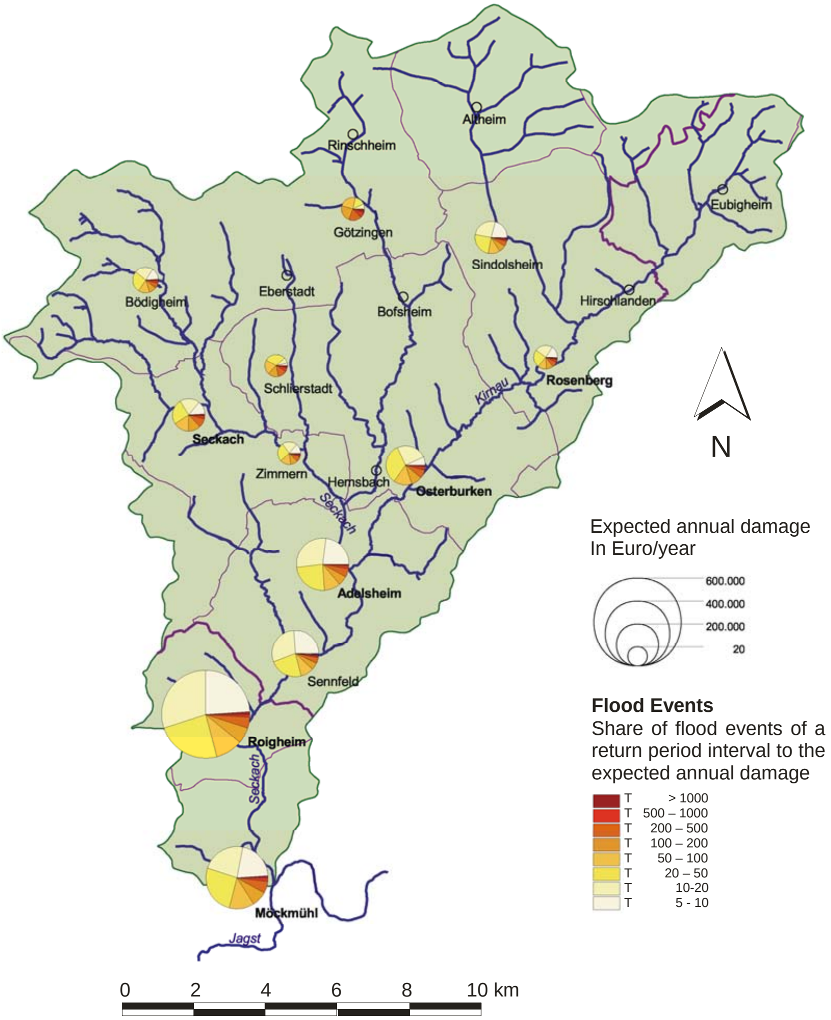

Fig. 2. Expected annual damage (EAD in Euro/year) for the municipalities in the Seckach catchment (adapted from Merz, 2006).

2.2 Case studies

The EAD concept, introduced in Sect. 2.1, is applied to three case studies from different regions in Germany. As first case study the catchment of the river Seckach with an area of 260 km^2 was chosen. It is situated in Southwest Germany, in the east of the city Heidelberg, in the Odenwald region. Seven municipalities with approximately 47 000 inhabitants, who live in several small towns and villages, are located in the study area (Fig. 2). In December 1993, the catchment was affected by severe flooding causing damage of 25 to 30 million DM. 13 months later, i.e. in January 1995, large flooding occurred again, which initiated an integrated flood defence planning. As a part of the planning process, several inundation scenarios with different return periods were derived and the damage was assessed for each scenario and for each settlement area. These calculations provided the basis for a benefit-cost-analysis of the planned flood protection scheme (Merz and Gocht, 2001).

Figure 2 shows the EAD for the twelve biggest towns in the Seckach catchment for the situation in 1993/95. The size of the pie charts is a measure of the magnitude of EAD. The pie slices illustrate the share of each interval between two return periods to the total amount of RI:

$$\Delta RI_j = \Delta P_j D_j \tag{5}$$

Although larger floods are associated with higher damage, their contribution to the expected annual damage may be rather low, due to their small probability weights ΔP_j. For example, more than 50% of EAD of Roigheim results from events with return periods between 5 and 20 yrs. In seven of the twelve settlements the contribution of events up to the 100-year flood amounts to more than 80% of the expected annual damage. Only in one settlement (i.e. Goetzingen) the events up to the 100-year flood account for less than 50% of the EAD (Fig. 2). In this municipality the main share of the assets is located rather far from the river, which means that significant damage is only caused by larger events.

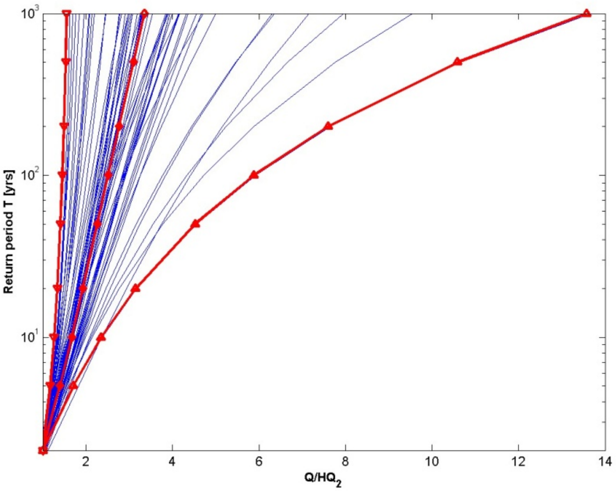

Fig. 3. Flood frequency curves from 56 gauging stations located in different catchments in Germany. The discharge Q was normalised by the median of the corresponding annual maximum series (AMS). The red curves highlight the mean as well as the minimum and maximum values.

In a more recent study (Olschewski, 2007), the EAD was calculated for two bigger municipalities that are located at the River Mulde in the Eastern part of Germany, i.e. in the Freestate of Saxony. In contrast to the rural municipalities of the Seckach study area, which has an average population density of 130 inhabitants per km^2, the two Saxon municipalities Doebeln and Eilenburg have a population density of 390 and 690 inhabitants per km^2, respectively. The two municipalities were hit by a severe flood event in August 2002, which caused 54.5 million Euro damage at residential buildings in Doebeln and 76.9 million Euro damage in Eilenburg (SAB, 2004).

Seven inundation scenarios, i.e. from the 10-year to the 1000-year flood event, were calculated using the 1-D/2-D-model LISFLOOD-FP (Bates and de Roo, 2000). Damage was estimated with five meso-scale damage models and three micro-scale damage models by Olschewski (2007). Although the damage estimates differed considerably, the share of the intervals between two return periods remained rather constant. On average, the events up to the 100-year flood contributed 77% to the expected annual damage in Doebeln, and 57% in Eilenburg. The latter can be explained by the fact that the city centre of Eilenburg is only flooded by rare events with return periods of more than 100 years. In all analyses, the interval between the 500-year and the 1000-year flood caused 6 to 12% of the expected annual damage.

Finally, the EAD was calculated for the City of Cologne, which is located at the River Rhine. Cologne has nearly 1 million inhabitants and a population density of 2390 inhabitants per km^2. The City of Cologne was also hit by floods in December 1993 and in January 1995; damage amounted to 77 million Euros and 33 million Euros, respectively. On the basis of the analysis done by Grünthal et al. (2006) and Merz and Thieken (2009), flood events up to the 100-year flood event cover a share of 78% of the expected annual damage. The share of the interval between the 500- and the 1000-year flood amounts to only 8% of the risk indicator.

In summary, in the mentioned case studies extreme events do not contribute much to EAD. The greatest proportion, approximately 80%, of the benefits of a flood protection system is attributed to the reduced damage due to more frequent events with return periods up to 100 years.

2.3 General considerations

The empirical results from the case studies led to the question whether the low share of "low probability/high damage" events to EAD is a general phenomenon of riverine flooding. This share depends on the relationships between water level h, discharge Q, return period T, and damage D. These relationships are determined by the rating curve $h(Q)$, the flood frequency curve $Q(T)$ or $h(T)$, and the stage-damage curve $D(h)$. In order to consider a wide range of cases, different assumptions were chosen for each of the mentioned functions. Moreover, the water level, at which the first damage occurs, h_D, plays an important role. This value was set to the 5-year flood event. Therefore, we concentrate on situations where no extensive flood protection schemes exist. In what follows, the interrelations of the different components are considered only for water levels that exceed h_D.

To consider a wide spectrum of flood frequency curves, Annual Maximum Series (AMS) were extracted from mean daily discharge measurements at 56 discharge gauges from all over Germany. The generalised extreme value distribution (GEV) was fitted to these data. Figure 3 shows the flood frequency curves that were normalised by the median of the corresponding AMS. The governing feature that determines the contribution of a return period interval to EAD is the parameter γ of the GEV. The frequency curves with the maximum and the minimum value of γ, i.e. 0.27 and -0.34, respectively, represent the most extreme behaviour of the 56 AMS. Therefore, these two functions together with the mean function (γ=0) were chosen for the further analysis (Fig. 3). To ensure comparability, all three functions were scaled so that all of them show the same discharge at the 5-year flood water level that corresponds to h_D.

Besides the flood frequency curve, the shape of the river valley influences the contribution of extreme events to EAD. Typical shapes of valleys in Germany were mapped by Germany's Environment Agency (Briem, 2003). This study reveals that most of German river valleys can be approximated by a linear or a concave shape. A linear shape represents V-shaped valleys, whereas the concave shape typifies (wide open) U-shaped valleys. In order to consider the whole spectrum of possible shapes, a convex shape was chosen as third example (Fig. 4).

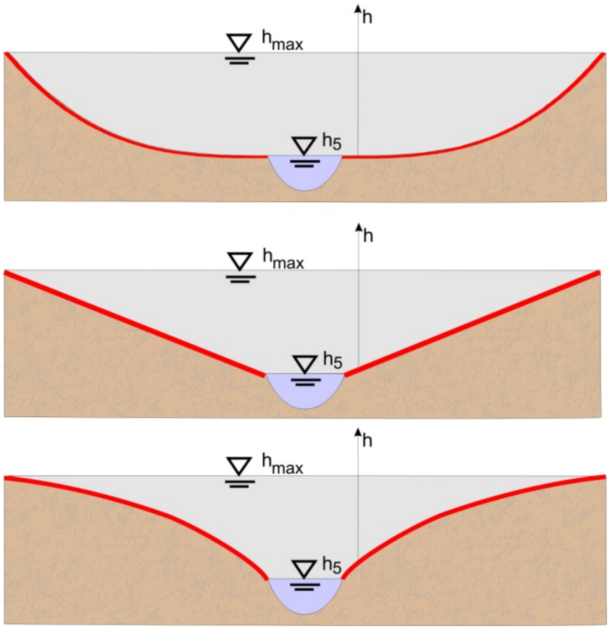

Fig. 4. Concave, linear and convex valley shapes.

Uniform, stationary flow was assumed for the derivation of the rating curves. By means of the Gaukler-Manning-Strickler equation the relation between the discharge outside the riverbed and the water level above h_D was calculated for each valley type (Fig. 5).

The relation between river water level and flood damage, i.e. stage-damage curve $D(h)$, depends on the valley type, and on the spatial distribution of the assets at risk and of their susceptibility. It was assumed that the assets as well as their relative susceptibility function were distributed uniformly. In municipalities, which experienced floods repeatedly and which therefore are likely to have a profound flood risk awareness, it would be expected that none or only low asset values can be found in the vicinity of rivers and/or that their susceptibility is low. High asset values and more susceptible objects are to be found farther away from the river. However, since no systematic and meaningful investigation of this topic is known to the authors, the simple assumption of a uniform distribution was chosen. Therefore, the amount of damage is proportional to the inundated area and the stage-damage curve is thus a result of the underlying valley type (Fig. 6).

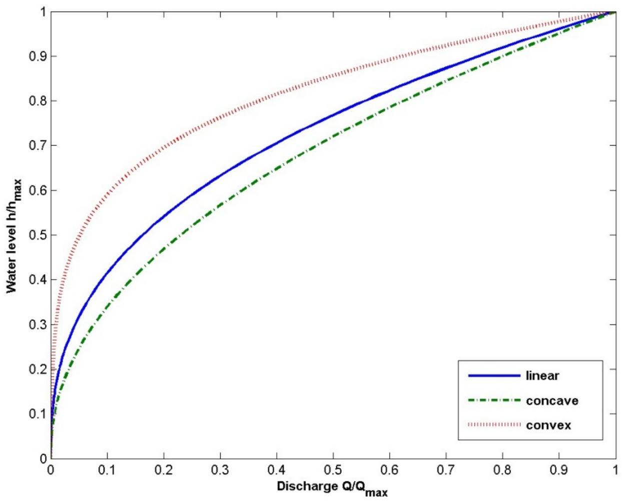

Fig. 5. Rating curves for the flood plains (area outside the river bed) considering three different valley types. Discharges and water levels are normalised by the respective maxima.

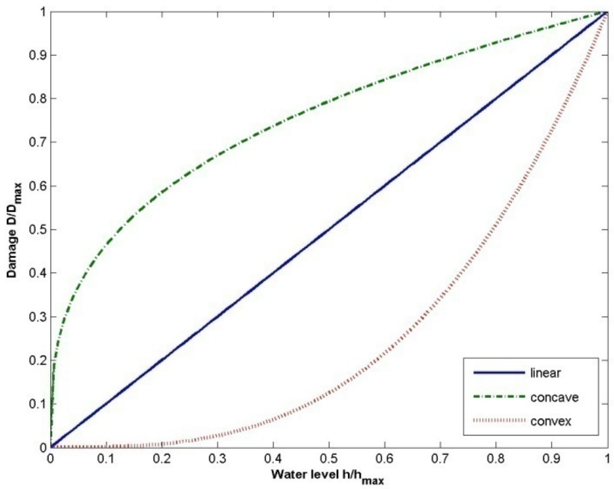

Fig. 6. Stage-damage curve $D(h)$ for the three valley types. Damage values and water levels are normalised by the respective maxima.

Nine different combinations result from the superposition of the different rating curves, stage-damage-functions and flood frequency distributions (three valley types times three GEV-curves). Their $h(T)$-functions, i.e. the relationship between river water level and return period, are shown in Fig. 7. The shares of the different return period intervals to EAD can be calculated on the basis of Eq. (4), and are shown in Fig. 8. It can be seen that the highest share to EAD can be assigned to frequent events in the case of the linear and the concave valley shape. On average, events of the interval 5–10 yrs contribute 28% to the expected annual damage, those of the 5–20 yrs interval 60%, and those of the 5–50 yrs interval 82%. On the contrary, extreme events play a minor role. For example, the share of events with a return period of more than 500 yrs amounts to 2%, that of events with a return period of more than 1000 yrs only to 1%.

In summary, the general considerations are consistent with the findings from the empirical case studies. However, in the case studies the share of "low probability/high damage" events tends to be a little higher than in the generalised cases.

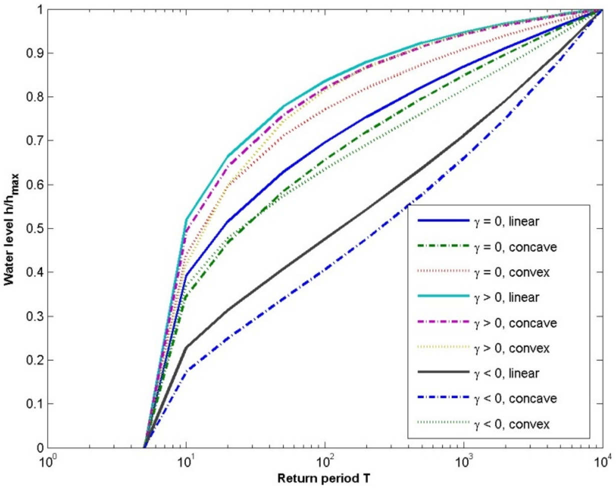

Fig. 7. Flood frequency curves $h(T)$ for the nine combinations of valley types and GEV-distributions. River water levels are normalised to the respective maximum.

We attribute this minor disagreement to our assumption that the asset distribution and susceptibility functions are uniform, i.e. that the distance to the river does not influence the asset and susceptibility distribution. In reality, it is likely that frequently flooded areas are kept free from settlements and other assets, or that objects in these areas have a lower susceptibility than those in less frequently affected areas.

3 Societal significance of “low probability/high damage” events

The considerations of Sect. 2 reveal that “low probability/high damage” floods contribute only to a small degree to EAD and should therefore be of small importance in flood risk decisions, if EAD was an adequate risk indicator. However, flood mitigation measures are often initiated as a consequence of “low probability/high damage” floods. This mismatch can be explained by the perception of risks. The societal significance of a risk is defined by how it is perceived. Differences in preference for decision alternatives were shown to be associated with different perceptions of the relative risk of the options, rather than with different attitudes towards the risk (Weber and Milliman, 1997; Slovic and Weber, 2002). Risk perception is context-dependent and is affected by social, political, cultural and economic factors (e.g. Kasperson et al., 1988; Pidgeon et al., 1992; Renn, 1998; Plattner et al., 2006). The variety of these factors and their interaction result in a strong variation of risk perception.

Although individuals perceive risks as complex, multidimensional phenomena, it has been shown that perceived risk is, to some extent, quantifiable and predictable, since every hazard has a unique pattern of qualities that appears to be related to its perceived risk (e.g. Slovic, 1987; Slovic and Weber, 2002; Grothmann and Reusswig, 2006). Subjective risk appraisal is not only defined by personal preferences or even irrational patterns, but follows sensible rules and should be considered in risk management (Bohnenblust and Slovic, 1998; Renn, 1998).

Slovic (1987) grouped 15 risk dimensions to two risk factors, “Dread Risk” and “Unknown Risk”. The perceived seriousness of a hazard is predictable from knowledge of where the hazard stands with regard to “Dread Risk” and “Unknown Risk” (Slovic et al., 1984). These factors help to explain the observation that society tends to be risk-averse, i.e. that the public appears to accept more readily a much greater social impact from many small accidents than it does from the more severe, less frequent occurrences that have a smaller societal impact (US Nuclear Regulatory Commission, 1975).

Risk aversion is linked to the social amplification of risk (Kasperson et al., 1988). This holds for events whose adverse effects, e.g. massive indirect impacts such as tightened regulation or loss of trust in authorities exceed the direct damage by far. While the size of the impact of an event does not necessarily determine its proneness to the process of social amplification, the event has to be of the high-signal type. Certain events, frequently events with the potential to affect a large number of people, are perceived as signals of future trouble. The social impact of an event will be large, regardless of its direct damage, if the event greatly increases the estimated risk of the activity or technology, e.g. raising fear that the activity is not adequately under control (Slovic et al., 1984). One implication is that effort and expense beyond that indicated by a traditional cost-benefit analysis might be warranted to reduce the possibility of high-signal events (Slovic and Weber, 2002).

Further, people dread “low probability/high damage events” more than their statistical importance implies, since such events may surpass the coping capacity of the affected element-at-risk. The concentration of adverse impacts in time and space may require a long-term effort to recover from the event, or even worse, the impact may be of such magnitude that the affected element-at-risk may be unable to cope with the adverse effects. Therefore, individuals, businesses or smaller groups are usually considered risk-averse, unless they are very wealthy and highly diversified, due to limited coping mechanisms that enable them to deal with high-damage events. However, Siegrist and Gutscher (2008) showed that people cannot predict the negative effects that are evoked by severe flooding (especially negative emotional consequences) and therefore do not invest in risk mitigation. Larger groups (large companies, countries, etc.) are often assumed to be risk-neutral due to their possibility to spread risks (Mechler, 2004). For example, the public sector is often considered as risk-neutral, as it can more easily share risks. Hence, cost-benefit analyses in the public sector are usually based on expected utility.

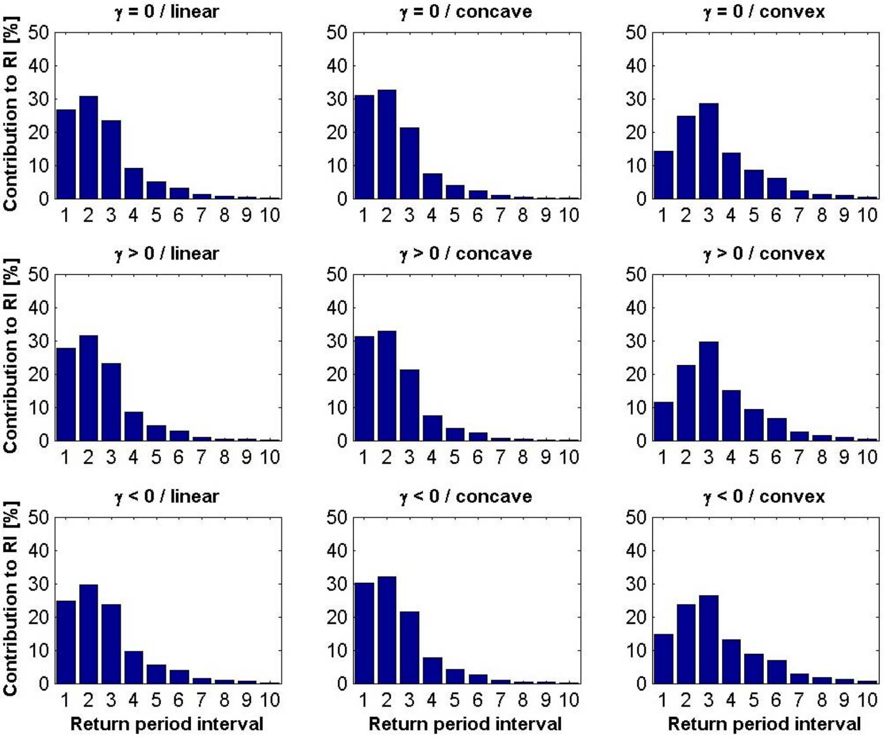

Fig. 8. Share (given in %) of the return period intervals to the expected annual damage (*RI*) for the nine combinations of valley types and GEV-distributions. (Considered return period intervals: 1: 5–10 yrs; 2: 10–20; 3: 20–50; 4: 50–100; 5: 100–200; 6: 200–500; 7: 500–1000; 8: 1000–2000; 9: 2000–5000; 10: 5000–10000 yrs).

However, it can be summarised that there are well legitimate reasons for putting a stronger emphasis on "low probability/high damage" events than their contribution to EAD suggests. The concept of EAD as risk indicator assumes risk neutrality and is inadequate, if risk aversion is important. Therefore, it is necessary to evaluate the implications of different risk preferences (risk neutral versus risk adverse) on decision-making.

4 Integrating risk aversion in decisions on flood risk mitigation

In this section risk aversion is integrated in the calculation of risk reduction for hypothetical flood defence measures for the three communities Cologne, Doebeln and Eilenburg introduced in Sect. 2.2. It is analysed how the inclusion of risk aversion changes the contribution of "low probability/high damage" events to *RI*, and how this may influence the decision on flood risk mitigation. For each community the current flood risk is described by flood risk curves, relating the flood damage in the community to return periods. In a second step the effects of flood protection through a dike system or, alternatively, an early warning system on these risk curves are calculated. These calculations are performed for risk-neutral and risk-averse behaviour. For both cases, it is compared to which extent each flood protection strategy reduces the risk.

This example uses only damages to the residential sector. This is the sector for which, at least in Germany, the most reliable data and damage models exist. Since we are interested in the question how risk aversion affects risk reduction and, consequently, risk mitigation decisions, this restriction to one economic sector does not limit the basic conclusions drawn from this example. The same approach could be applied in a more comprehensive risk assessment. With the FLEMOps damage estimation model for the residential sector that was derived from actual damage data collected after the 2002 floods in the Elbe and Danube catchment (Thieken et al., 2008) and asset values in terms of disaggregated replacement costs per community for residential buildings (Kleist et al., 2006; Thieken et al., 2006), the damages in the residential sector are estimated for seven flood scenarios (return periods: 10, 20, 50, 100, 200, 500, 1000 years). These results are taken from Olschewski (2007), and Merz and Thieken (2009). To be able to compare the three municipalities, relative damage is used as damage indicator. It is calculated by relating the (scenario-) damage to the residential asset values in the communities. To extend the probability range, these risk curves are extrapolated for the return periods 2000, 5000 and 10 000 years.

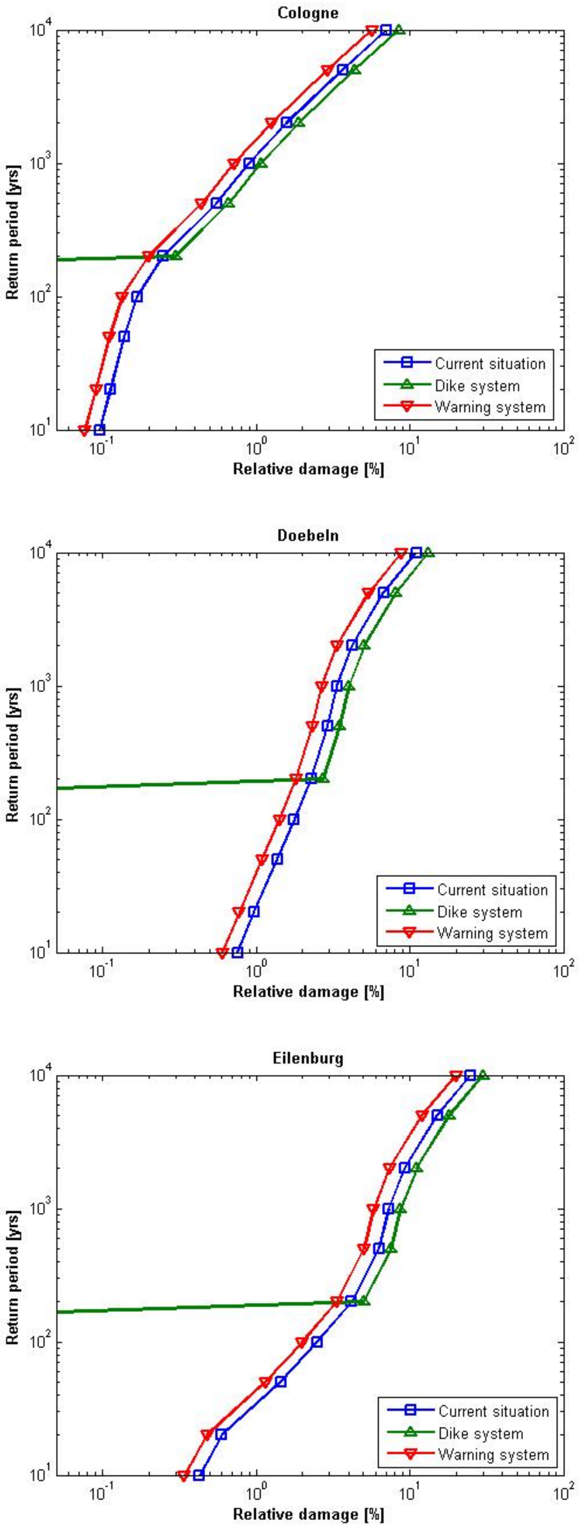

Fig. 9. Risk curves for Cologne (top), Doebeln (middle) and Eilenburg (bottom).

Figure 9 shows the resulting risk curves (curves named “current situation”) for the three communities. For the considered range of return periods (10–10 000 yrs), the relative damage varies from 0.09% to 7% for Cologne, from 0.8% to 11% for Doebeln, and for 0.4% to 25% for Eilenburg. For the smaller municipalities, relative damages for similar return periods are higher than for Cologne.

For each community the risk reduction due to flood mitigation is calculated. Two mitigation options, namely flood warning and protection by dikes, are chosen. This choice is motivated by the different characteristics of these mitigation options. Flood defence by dikes is a typical representative of the resistance strategy, whereas flood early warning represents the resilience strategy. Resistance strategies aim at reducing the flood hazard, i.e. the frequency of flooding, and are traditionally called flood control strategies, whereas resilience strategies rather aim at learning to live with the floods (Vis et al., 2003).

The dike system is assumed to fully protect the municipality and prevent all damages up to a return period of 200 years. In Germany, dikes are frequently designed for the 100-year flood. By adding a freeboard of 0.5 to 1.0 m, the safety level of many dikes in Germany is approximately 200 years. For larger events the dike system is expected to fail. Since dikes eliminate inundations in the dike hinterland for events lower than the failure flood (200 yrs), residents of the dike hinterland tend to develop a feeling of safety and an increase in assets and a decrease in flood susceptibility in dike-protected areas is a common phenomenon. To take this effect (called “levee effect” according to Tobin, 1995) into account, an increase in asset values behind dikes is assumed as a consequence of the dike system. Based on these assumptions, the risk curves for the mitigation option “dike system” have a common form: no flood damage below the failure flood (200 yrs), whereas the damage above the failure flood is increased, compared to the current situation. Figure 9 shows the risk curves for an increase of 20%.

Although the effect of increasing asset values in the dike hinterland is frequently mentioned (e.g. Tobin, 1995), there is hardly any data available. The studies of McMasters (1996) and USACE (2004) on the development in US floodplains indicate that this “levee effect” could be in the order of 5–10%. In some special places, e.g. New Orleans, this effect could be much higher (Burby, 2006). Due to the lack of quantitative statements, two scenarios (5% and 20%) are investigated which are seen as plausible range.

As an alternative mitigation measure, a flood warning system including public awareness campaigns is proposed. Unlike dike protection, early warning systems do not fully eliminate damages, but the damage-reducing effects work for low- and high-probability events alike. The extent of the damage reduction is difficult to quantify. Several surveys (Lustig et al., 1988; Queensland Gov., 2002; Parker, 2007) have dealt with this problem. The ability to efficiently perform protection measures which are undertaken after a flood warning has been received strongly depends on the knowledge about self-protection, which is connected to the quality of flood warning information as well as to prior flood experience, residents' homeownership and household size (Thieken et al., 2007). A damage-reducing effect of 20% is assumed which is on the upper side of the percentages found in empirical studies and proposed in the literature (Kreibich et al., 2005). Such a relatively high efficiency requires the residents to be aware of the threat and of the possibilities for effective emergency measures. Therefore, we assume that the operation of the early warning systems is combined with measures for raising and maintaining a high awareness among the flood-prone residents. Figure 9 shows the shifting of the current risk curve towards lower damage as a consequence of a well-maintained flood warning system that motivates residents to perform damage-reducing activities in case of warnings.

In the following, the contribution of the different flood scenarios, with return periods from 10 to 10 000 years, to the overall risk and to the damage reduction for the two mitigation measures (dike system, flood warning system) are calculated. This is done for risk-neutral and risk-averse behaviour.

In this example, risk aversion is assumed to be a function of the relative damage of the municipalities. They are seen as the entity for which the decision on flood mitigation is made. Risk aversion should only be taken into account if a considerable part of the municipality is at risk. The municipality should be interested in avoiding high-signal events that trigger strong public concern and have high societal impact and in situations where its coping capacity might be surpassed. Therefore, the ratio of damage to the assets of the municipality can serve as indicator for risk aversion.

In the risk literature two risk aversion models are applied, the multiplicative one (Eq. 6) and the exponential model (Eq. 7):

$$RI^* = \sum_{j=1}^{m} \Delta P_j D_j \alpha(D_j) \tag{6}$$

$$RI^* = \sum_{j=1}^{m} \Delta P_j D_j^{\beta} \tag{7}$$

Both models are variants of the traditional risk equation (Eq. 2). In both models risk aversion is considered by introducing a risk aversion factor α or β, respectively. They can be interpreted as a penalty function which overproportionally weighs events with large damage. The resulting risk measure RI^* can be considered as perceived societal risk (Bohnenblust and Slovic, 1998).

Risk aversion models are usually applied to multiple-fatality accidents (e.g. Slovic et al., 1984; Hubert et al., 1991; Mechler, 2004; Abrahamsson and Johansson, 2006). For example, the exponential model is based on a utility model stating that the societal cost (or disutility) of N lives lost in a single accident is a function of N^{β} (Slovic et al., 1984). Three general forms can be differentiated: $\beta>1$ (risk-averse), $\beta=1$ (risk-neutral), $\beta<1$ (risk-seeking). The exponential and multiplicative models are related ($\alpha(D)=D^{\beta-1}$), and can be used interchangeably. Although there has been an intense discussion on risk aversion, empirical studies on people's risk preferences regarding multiple fatalities are rare (Abrahamsson and Johansson, 2006).

We apply risk aversion functions to economic damage estimates. In Germany the number of casualties resulting from river floods is fortunately low and does not play an important role in the public discussion about flood risk. This discussion is mainly steered by direct economic damage. This is also the only flood damage type for which substantial data and models are available in Germany. Therefore, economic damage is used as damage type, although we are aware of the importance of other loss dimensions such as adverse psychological effects.

The parameterisation of risk aversion models is a subjective process and reflects value judgements (Bohnenblust and Slovic, 1998). Mechler (2004) summarises the empirical work on risk aversion and states that evidence concerning risk aversion remains inconclusive. Data on the preference of the respective decision makers are necessary but frequently not readily available (Mechler, 2004), and risk aversion functions are not the same for different hazards (Bohnenblust and Slovic, 1998). Recently, Abrahamsson and Johansson (2006) studied risk preferences of experts in the risk management sector, related to accidents or other situations with the possibility of multiple fatalities. Surprisingly, the majority of the subjects showed risk-seeking behaviour. They accepted the risk of highly serious consequences to retain the possibility of the adverse impacts being much less serious. One recurring argument was that, when the number of fatalities had reached a certain point, a further increase did not affect the perception of the scenario. There might be a threshold beyond which an event is simply seen as catastrophic without further discrimination. Most of the participants with risk neutral preferences argued that the expected number of facilities ought to be used in a normative sense in decision making, since they considered it as the most rational approach. This example highlights that diverging views on risk aversion exist. Depending on the context of the risk situation, different stakeholders might have different views on risk aversion. Therefore, the issue of risk aversion needs to be carefully scrutinised in each risk evaluation.

In our example the multiplicative risk aversion model is used, based on the following assumptions:

- Risk aversion increases with the relative damage, i.e., events where larger fractions of the assets within a municipality are destroyed are penalised.

- The risk aversion function contains two thresholds. The lower threshold D_L defines the relative damage above which risk aversion is assumed. The upper threshold

Table 1. Assumptions underlying the four risk aversion models and the effects of flood protection measures.

Risk aversion model	Risk aversion factor α	Relative residential damage		Effects of protection measures	
		lower threshold	upper threshold	Dike	EWS
M0	1			5% or 20% increase of asset values behind dikes	20% damage reduction
M1	10	1%	20%		
M2	10	1%	10%		
M3	50	1%	10%		

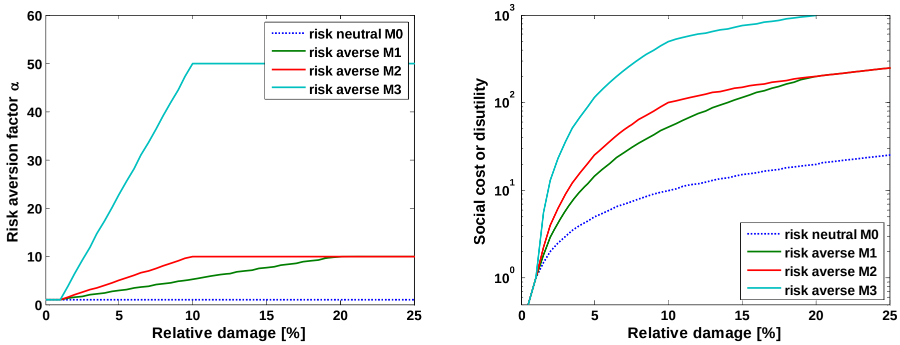

Fig. 10. Risk aversion functions at the level of municipalities: risk aversion factor as function of relative damage (left) and disutility functions (right).

D_U defines the damage above which risk aversion does not increase anymore. The risk aversion factor α increases linearly between D_L and D_U.

Figure 10 shows the chosen risk aversion factors, and Table 1 lists the assumptions underlying the risk aversion models and the effects of protection measures. Besides the risk-neutral approach (model M0), three risk-averse models (M1–M3) are given. All risk-averse models have the same lower threshold of 1%, i.e. risk aversion is not considered for events with direct damage lower than 1% of the total assets in the community. The upper threshold is set to 10% and 20%, respectively, since only a partition of the municipality values are at risk of flooding and even those values at risk are in most cases not fully destroyed. 10% or 20% damage seems to be an event that is perceived as devastating for riverine flood in Germany. A rough estimate based on asset values and damage data from SAB results in a relative residential damage for the August 2002 flood of approximately 5.5% for Doebeln, 10% for Eilenburg, and 1% for Dresden. This flood can be characterised as a high-signal event. It triggered a nation-wide discussion on flood risk management, and a number of extensive consequences followed (Petrow et al., 2006). The maximum risk aversion factor $\alpha_{\max}$ is more difficult to choose. Other studies have used values up to 8 (railroad crossings, PLANAT, 2007), 10 (railway accidents, natural disasters, Bohnenblust and Slovic, 1998; BABS, 2003; PLANAT, 2005), 15 (avalanche risk, BUWAL, 1999), 30 (railway tunnels, PLANAT, 2007), or 100 (natural disasters, BABS, 2003). Bründl (2009) suggests a function where risk aversion is composed of multiple factors resulting in an overall maximum risk aversion factor of approx. 15 for small to large events and approx. 50 for extreme loss events. Based on these studies, we assume $\alpha_{\max}$=10 (M1, M2) and 50 (M3), respectively.

The chosen risk aversion model and its parameters are not meant to reflect the preferences of decision makers. For example, the range of aversion factors is taken from risks involving fatalities. The transfer of these values to economic risk is questionable. In a real-world application, these issues would have to be discussed with the responsible decision makers. The objective of our example is to illustrate how the consideration of risk aversion may influence flood mitigation decisions. Hence, it suffices to choose plausible realisations of risk aversion functions. Since uncertainties in eliciting risk aversion parameters are large, it is appropriate to use a range of values for illustrating the effect of risk aversion on decision-making (Mechler, 2004).

Applying the multiplicative risk aversion model (Eq. 6) and the aversion functions of Fig. 10, the contribution of flood scenarios to the total risk is calculated for each municipality and each mitigation scenario (current status, dike system, warning system). The risk indicator used is the per-

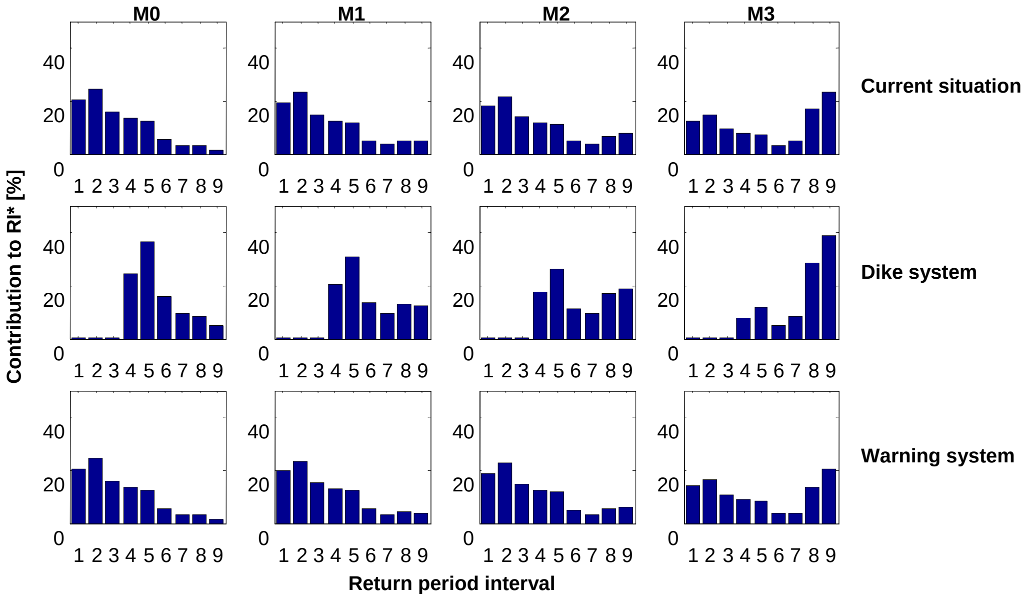

Fig. 11. Share (given in %) of the return period intervals to the perceived societal risk (*RI**) for four risk aversion models (M0–M3) and three mitigation strategies (current situation: top row; dike system: middle row; warning system: bottom row) for Eilenburg. A levee effect of 20% is assumed. (Considered return period intervals: 1: 10–20; 2: 20–50; 3: 50–100; 4: 100–200; 5: 200–500; 6: 500–1000; 7: 1000–2000; 8: 2000–5000; 9: 5000–10 000 yrs).

ceived societal risk *RI**. As example, Fig. 11 gives the percentage to which each return period interval contributes to *RI** for Eilenburg and an increase of asset values in the dike hinterland of 20%. Comparing the three mitigation options, it is obvious that the relative contribution of the return period intervals is the same for the current situation and for the early warning system. For the dike system the return period intervals 1–3 ($T<100$ yrs) do not contribute, since the dike system fully protects against flooding.

More important is the comparison of the four risk aversions models. For the risk-neutral model M0, the high probability events dominate the overall risk. As soon as risk aversion is included, the contribution of low probability events increases. This may lead to bimodal distributions (e.g. model M2 and dike system) or even to reversed distributions (e.g. model M3 and dike system). Assuming risk aversion with $\alpha_{\max}$=10 (models M1, M2) leads partially to significant changes and partially to minor ones. $\alpha_{\max}$=50 changes dramatically the contribution of low probability events.

Finally, the benefit due to the two mitigation options (dike system, warning system) is quantified. This benefit is calculated as the annual risk reduction after the implementation of the mitigation options:

$$\Delta RI_D^* = RI_D^* - RI_D^* \quad \text{and} \quad \Delta RI_W^* = RI_C^* - RI_W^* \qquad (8)$$

where *RI** denotes the perceived societal risk and the subscripts denote the mitigation options: C – current situation; D – dike system; W – warning system. Table 1 shows $\Delta RI_D^* = RI_D^*$ and ΔRI_W^* for the four risk aversion models and for the two levee effect scenarios. For the risk-neutral model (M0), the risk reduction due to the dike system is significantly larger than the reduction due to the warning system. This is valid for both levee effect scenarios. However, the introduction of risk aversion changes this pattern: the risk reduction due to the dike system decreases, and the one due to the warning system increases. This pattern is explained by the fact that the warning system also decreases damages of low probability floods, whereas the dike system only mitigates higher probability floods. The risk reduction due to the dike system also depends on the assumption on the levee effect. For a levee effect of 5% and the communities Doebeln and Eilenburg, the risk reduction due to the dike system is larger than the one due to the warning system, regardless of the risk aversion model. For a levee effect of 20% and the risk aversion model M3, the warning system would provide a larger risk reduction for Eilenburg.

The effect of M3, the model with the strongest risk aversion, is quite dramatic. For Cologne and Eilenburg and a levee effect of 20%, the order of the mitigation options is reversed compared to the risk-neutral model: the risk reduction due to the warning system is significantly larger than the one due to the dike system. Interestingly, the dike system risk reduction for Cologne is negative, if risk aversion model M3 is applied. This is a consequence of the 20% increase of potential damage as effect of the dike system and of the higher weights that are associated with low probability events. This means that the dike system increases the annual risk, if the assumptions (20% potential damage increase, strong risk aversion M3) are deemed to be plausible.

Table 2. Annual benefits (ΔRI^* in millions of €) of two mitigation options for three municipalities, four risk aversion models and two scenarios of the levee effect.

Risk aversion model	Doebeln			Eilenburg			Cologne		
	Dike		EWS	Dike		EWS	Dike		EWS
	5%	20%		5%	20%		5%	20%	
M0	0.97	0.94	0.24	0.62	0.57	0.19	5.13	4.81	1.48
M1	0.97	0.92	0.25	0.61	0.54	0.22	5.02	4.33	1.84
M2	0.96	0.90	0.27	0.60	0.50	0.25	4.90	3.79	2.25
M3	0.92	0.71	0.41	0.53	0.18	0.49	3.89	−0.72	5.70

5 Conclusions

Flood risk analyses and flood cost-benefit studies usually apply the technical concept of risk and EAD is used as risk indicator. This paper shows that, for riverine floods in Germany, EAD is dominated by "high probability/low damage" events. For all case studies (the Seckach catchment area and three other municipalities in Germany), approximately 80% of the potential benefits of a flood protection system has to be attributed to the reduced damage due to frequent events with return periods of up to 100 yrs. General considerations, based on typical values for flood frequency behaviour, flood plain morphology, etc., support these findings. Using the concept of EAD, "low probability/high damage" events play a minor role. For example, the share of events with a return period of more than 500 yrs amounts typically to 2%, that of events with a return period of more than 1000 yrs to 1%.

These results are in contrast with the perception of "low probability/high damage" flood events. People tend to dread events that might cause very high damage, and there are well-founded arguments for this view. Such events can significantly influence the long-term development of regions, communities or individual livelihoods. They may be associated with follow-up effects that extend far beyond the direct effects that are usually accounted for in risk analyses. Hence, in flood risk studies EAD should be used with care. It may not be a prudential risk indicator, since it is not always congruent with well-founded societal risk priorities.

Since this mismatch between technical risk appraisals and the perception of society stems from the limitations of today's flood risk analyses, a larger emphasis should be placed on considering indirect, intangible and long-term consequences of floods. If a complete quantification of all flood impacts in a technical risk analysis were possible, this mismatch would be closed.

Realistically, a complete quantification is a long way ahead. Therefore, attempts to compensate the effects of missing consequences are valuable. To this end, risk aversion may be included in the risk assessment, trying to quantify the perceived societal risk instead of the technical risk. A proposal is made to consider risk aversion, based on quasi-monetary values, for flood mitigation at the municipality level. We argue that risk aversion depends on the scale of the loss. The relative damage, i.e. event loss divided by the total assets in the municipality at risk, is proposed as measure for assigning risk aversion factors to flood events.

The introduction of risk aversion penalises events with disastrous consequences. This preference of avoiding devastation instead of minimising EAD has implications for the appraisal of risk mitigation options. It is shown that the annual risk reduction due to alternative mitigation options may be very differently assessed. Applying the "classical" EAD approach (risk-neutral), flood protection by dikes has large positive benefits in the three municipalities studied. They are much larger than the risk reduction due to a well-functioning flood warning system. However, the consideration of risk aversion decreases the positive effects of the dike system and increases the benefit of the warning system. Assuming the most pronounced risk aversion model and an increase of asset values behind dikes of 20%, the risk reduction of the dike system is even negative for Cologne. This result is, besides the large weights of low probability events in this risk aversion model, the effect of a comparatively large increase in potential flood damage in the hinterland area of the dike as a consequence of the perceived safety against (low probability) flooding.

Examples for the inclusion of risk aversion in flood risk studies are extremely rare. The quantification of risk aversion is a subjective process, reflects value judgments and depends on the context of the risky situation. In view of the inconclusiveness of the discussion on risk aversion, the risk aversion functions chosen in this study have to be taken with care. For example, the use of the relative damage as indicator for risk aversion needs further discussion. In large cities a comparatively small relative, but high absolute damage may be perceived as high-signal event. Therefore, it may be wise to adapt risk aversion functions, depending on the scale of the municipality. To understand these issues, more research on people's preferences in different risk contexts is necessary.

Although we are aware of the limitations of this investigation, we show that risk aversion may have substantial implications for the appraisal of flood mitigation. The resilience approach (flood warning system) is much more positively evaluated when risk aversion is considered. In contrast, the risk reduction effect of the resistance approach (dike system) diminishes with consideration of risk aversion. Different flood mitigation decisions are probable, when risk aversion is taken into account.

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References

Abrahamsson, M. and Johansson, H.: Risk preferences regarding multiple fatalities and some implications for societal risk decision making – an empirical study, Journal of Risk Research, 9(7), 703–715, 2006.

Asbeck, E. L. and Haimes, Y. Y.: The partitioned multiobjective risk method (PMRM), Large Scale Syst., 6(1), 13–38, 1984.

BABS: Katastrophen und Notlagen in der Schweiz (KATARISK). Eine Risikobeurteilung aus der Sicht des Bevölkerungsschutzes, Bundesamt für Bevölkerungsschutz (BABS), 83 pp., 2003.

Bates, P. D. and de Roo, A. P. J.: A simple raster-based model for flood inundation simulation, J. Hydrol., 236(1–2), 54–77, 2000.

Bohnenblust, H. and Slovic, P.: Integrating technical analysis and public values in risk-based decision making, Reliab. ENG. SYST. Safe., 59, 151–159, 1998.

Briem, E.: Gewässerlandschaften der Bundesrepublik Deutschland, ATV-DVWK-Arbeitsbericht, 2003.

Bründl, M. (Ed.): Risikokonzept für Naturgefahren - Leitfaden. Testversion Februar 2009, Nationale Plattform für Naturgefahren (PLANAT), Bern, 420 pp., 2009.

Burby, R. J.: Hurricane Katrina and the paradoxes of government disaster policy: Bringing about wise governmental decisions for hazardous areas, The Annals of the American Academy of Political and Social Science, 604, 171–191, 2006.

BUWAL: Praxishilfe. Kosten-Wirksamkeit von Lawinenschutz-Massnahmen an Verkehrsachsen, Bundesamt für Umwelt, Wald und Landschaft (BUWAL), Bern, 1999.

Dawson, R. and Hall, J.: Performance-based management of flood defence systems, Water Management, Issue WMI, 157, 35–44, 2004.

Eckstein, O.: Water resource development: the economics of project evaluation, Harvard University Press, Cambridge, Mass., 110–159, 1958.

Grothmann, T. and Reusswig, F.: People at risk of flooding: Why some residents take precautionary action while others do not, Nat. Hazards, 38(1–2), 101–120, 2006.

Grünthal, G., Thieken, A. H., Schwarz, J., Radtke, K., Smolka, A., and Merz, B.: Comparative risk assessment for the city of Cologne, Germany – storms, floods, earthquakes, Nat. Hazards, 38(1–2), 21–44, 2006.

Haimes, Y. Y.: Risk modelling, assessment and management, John Wiley, New York, 1998.

Hergarten, S.: Aspects of risk assessment in power-law distributed natural hazards, Nat. Hazards Earth Syst. Sci., 4, 309–313, 2004, http://www.nat-hazards-earth-syst-sci.net/4/309/2004/.

Hubert, P., Barny, M. N., and Moatti, J. P.: Elicitation of decision-makers' preferences for management of major hazards, Risk Anal., 11(2), 199–206, 1991.

Jonkman, S. N. and Kelman, I.: An analysis of the causes and circumstances of flood disaster deaths, Disasters, 29(1), 75–97, 2005.

Karlsson, P.-O. and Haimes, Y. Y.: Risk-based analysis of extreme events, Water Resour. Res., 24(1), 9–20, 1988.

Kasperson, R. E., Renn, O., Slovic, P., Brown, H. S., Emel, J., Goble, R., Kasperson, J. X., and Ratick, S.: The Social Amplification of Risk: A Conceptual Framework, Risk Analysis, 8, 177–187, 1988.

Kleist, L., Thieken, A. H., Köhler, P., Müller, M., Seifert, I., Borst, D., and Werner, U.: Estimation of the regional stock of residential buildings as a basis for a comparative risk assessment in Germany, Nat. Hazards Earth Syst. Sci., 6, 541–552, 2006, http://www.nat-hazards-earth-syst-sci.net/6/541/2006/.

Kreibich, H., Thieken, A. H., Petrow, Th., Müller, M., and Merz, B.: Flood loss reduction of private households due to building precautionary measures – lessons learned from the Elbe flood in August 2002, Nat. Hazards Earth Syst. Sci., 5, 117–126, 2005, http://www.nat-hazards-earth-syst-sci.net/5/117/2005/.

Lustig, T. L., Handmer, J. W., and Smith, D. I.: The Sydney Floods of 1986: Warnings, Damages, Policy and the Future, Hydrology and Water Resources Symposium, Canberra, 1988.

McMasters, S.: The influence of structural flood control structures on the level of development in Midwestern Floodplains, Master thesis, 1996.

Mechler, R.: Natural disaster risk management and financing disaster losses in developing countries, Verlag für Versicherungswirtschaft, Karlsruhe, 2004.

Merz, B.: Hochwasserrisiken. Grenzen und Möglichkeiten der Risikoabschätzung, E. Schweizerbart'sche Verlagsbuchhandlung, Stuttgart, 334 pp., 2006.

Merz, B. and Gocht, M.: Risikoanalyse Seckach/Kirnau, Teil II: Ermittlung von Schadenspotentialen. Nutzen-Kosten-Analyse, Unpublished report, GeoForschungsZentrum Potsdam, 87 pp., 2001.

Merz, B. and Thieken, A. H.: Flood risk curves and uncertainty bounds, Nat. Hazards, submitted, 2009.

Olschewski, A.: Abschätzung von Hochwasserschäden an Wohngebäuden – ein Modellvergleich, Diploma thesis, Humboldt Universität zu Berlin, 109 pp., 2007.

Parker, D., Tapsell, S., and McCarthy, S.: Enhancing the human benefits of flood warnings, Nat. Hazards, 43, 397–414, 2007.

Penning-Rowsell, E. C. and Green, C.: Enhanced appraisal of flood alleviation benefits, in: Floods, Routledge Hazards and Disasters

Series, edited by: Parker, D. J., London and New York, 214–237, 2000.

Petrow, T., Thieken, A. H., Kreibich, H., Merz, B., and Bahlburg, C. H.: Improvements on flood alleviation in Germany: Lessons learned from the Elbe flood in August 2002, Environ. Manage., 38(5), 717–732, doi:10.1007/s00267-005-6291-4, 2006.

Pidgeon, N., Hood, C., Jones, D., Turner, B., and Gibson, R.: Risk perception, in: Royal Society Study Group Risk: Analysis Perception and Management, Royal Society, London, 89–134, 1992.

PLANAT: Strategie Naturgefahren Schweiz, Synthesebericht, Nationale Plattform Naturgefahren (PLANAT), Bern, 88 pp., 2005.

PLANAT: Risikoaversion. Entwicklung systematischer Instrumente zur Risiko- bzw. Sicherheitsbeurteilung bei naturbedingten und technischen Risiken. Phase 1: Darstellung und Analyse heute verwendeter Ansätze, Bundesamt für Bevölkerungsschutz (BABS), Nationale Plattform Naturgefahren (PLANAT), Bern, 2007.

Plattner, Th., Plapp, T., and Hebel, B.: Integrating public risk perception into formal natural hazard risk assessment, Nat. Hazards Earth Syst. Sci., 6, 471–483, 2006, http://www.nat-hazards-earth-syst-sci.net/6/471/2006/.

Queensland Government: Disaster loss assessment guidelines, State of Queensland and Commonwealth of Australia, 127 pp., 2002.

Renn, O.: The role of risk perception for risk management, Reliab. Eng. Syst. Safe., 59, 49–62, 1998.

Rose, A., Porter, K., Dash, N., Bouabid, J., Huyck, C., Whitehead, J. C., Shaw, D., Eguchi, R. T., Taylor, C., McLane, T. R., Tobin, L. T., and Ganderton, P. T.: Benefit-Cost Analysis of FEMA Hazard Mitigation Grants, Nat. Hazards Rev., 8(4), 97–111, 2007.

SAB (Saxon Relief Bank): Fördermitteldatenbank Hochwasser 2002, data as of 2004.

Sayers, P. B., Hall, J. W., and Meadowcroft, I. C.: Towards risk-based flood hazard management in the UK, Civil Eng., 150(5), 36–42, 2002.

Siegrist, M. and Gutscher, H.: Natural hazards and motivation for mitigation behavior: People cannot predict the affect evoked by a severe flood, Risk Anal., 28(3), 771–778, 2008.

Slovic, P.: Perception of Risk, Science, 236, 280–285, 1987.

Slovic, P., Lichtenstein, S., and Fischhoff, B.: Modeling the societal impact of fatal accidents, Manage. Sci., 30(4), 464–474, 1984.

Slovic, P. and Weber, E. U.: Perception of Risk Posed by Extreme Events. Paper prepared for discussion at the conference "Risk Management Strategies in an Uncertain World", Palisades, New York, 12–13 April, 2002.

Tapsell, S. M. and Tunstall, S. M.: The health and social effects of the June 2000 flooding in the north east region: report to the Environment Agency, Enfield, Flood Hazard Research Centre, Middlesex University, 2001.

Thieken, A. H., Kreibich, H., Müller, M., and Merz, B.: Coping with floods: preparedness, response and recovery of flood-affected residents in Germany in 2002, Hydrol. Sci. J., 52(5), 1016–1037, 2007.

Thieken, A. H., Müller, M., Kleist, L., Seifert, I., Borst, D., and Werner, U.: Regionalisation of asset values for risk analyses, Nat. Hazards Earth Syst. Sci., 6, 167–178, 2006, http://www.nat-hazards-earth-syst-sci.net/6/167/2006/.

Thieken, A. H., Olschewski, A., Kreibich, H., Kobsch, S., and Merz, B.: Development and evaluation of FLEMOps – a new Flood Loss Estimation MOdel for the private sector, Flood Recovery, Innovation and Response, 118, 315–324, 2008.

Tobin, G. A.: The levee love affair: A stormy relationship, Water Resour. Bull., 31, 359–367, 1995.

USACE (US Army Corps of Engineers, Tennessee Valley Authority): An economic evaluation of proposed flood protection plans on the Upper Mississippi River and Illinois Waterway, Report prepared for The Rock Island District, 2004.

US Nuclear Regulatory Commission: Reactor safety study. An assessment of accident risks in US commercial nuclear power plants, WASH 1400 NUREG-75/014, The Commission, Washington DC, 1975.

van Manem, S. E. and Brinkhuis, M.: Pilot case flood risk, in: Applications of statistics and probability in civil engineering, edited by: Der Kiureghian, A., Madanat, S., and Pestana, J. M., Millpress, Rotterdam, 881–887, 2003.

Vis, M., Klijn, F., de Bruijn, K., van Buuren, M.: Resilience strategies for flood risk management in the Netherlands, Intl. J. River Basin Management, 1(1), 33–40, 2003.

Weber, E. U. and Milliman, R.: Perceived risk attitudes. Relating risk perception to risky choice, Manage. Sci., 43, 122–143, 1997.