Synthesis Report

Assessment of upstream flood risk in the Rhine Basin (HSGR02)

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Ministerie van Infrastructuur en Milieu
Kennis voor Klimaat
Deltares
Enabling Delta Life

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KfC 100/2013

ISBN/EAN: 978-94-90070-70-0

This research project (HSGR02**Error! Use the Home tab to apply zKvkNummer to the text that you want to appear here.Error! Use the Home tab to apply zRapTitel to the text that you want to appear here.**) was carried out in the framework of the Dutch National Research Programme Knowledge for Climate (www.knowledgeforclimate.org) This research programme is co-financed by the Ministry of Infrastructure and the Environment, with special thanks to mr. Harold van Waveren and mr. Hendrik Buiteveld.

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Summary

This research shows that the risk from extreme flood events along the Rhine will not be stationary and might increase considerably during the coming decades. The implementation or strengthening of flood defense measures, such as retention basins and dike heightening, might prevent the increase in flood probability and thus the contribution of climate change to future flood risk. It was found that the annual expected damage in the Rhine basin may increase by between 54% and 230%, of which the major part (~ three-quarters) can be accounted for by climate change. The highest current potential damage can be found in the Netherlands (110 billion €), compared with the second (80 billion €) and third (62 billion €) highest values in two areas in Germany.

Information on the long-term development of private flood mitigation measures by households is important. Data from a survey along households along the Rhine in Germany shows direct disaster experience is an important trigger for the implementation of flood mitigation measures. A significantly increased rate of implementation can be consistently observed in the aftermath of flood events between 1980 and 2011. In addition, it is indicated that also workshops offered to flood-prone households by civil society and international river basin organisations, which emphasize the need for precautionary behaviour, can be a successful mechanism to increase the level of preparedness of flood-prone households. As far as the current implementation level of flood mitigation measures is concerned, it is found that a considerable share of respondents did not implement a single flood mitigation measure, despite a high vulnerability of the surveyed households to floods.

The damage-reducing effect of flood mitigation measures was examined by comparing the precautionary behaviour and damage suffered of households that were affected by two severe floods in 1993 and 1995. This comparison demonstrated that the substantial damage reduction observed in 1995 can indeed be attributed to an improved preparedness of the flood-prone population during the latter event. Moreover, it is found find that even respondents who did not undertake any precautionary measure themselves in 1993 and 1995, still benefitted from the improved preparedness of others due to lower levels of contaminated flood waters.

In order to effectively stimulate flood precautionary behaviour, better knowledge about the factors that influence individual's decisions to protect themselves against flood impacts is therefore essential for risk communications. Such effective risk communication is needed to increase the preparedness of the population facing flood risk in order to successfully manage the transition from traditional flood control approaches to integrated flood-risk management in Europe and worldwide. The review of 16 peer-reviewed studies examining the relation between flood risk perceptions and mitigation behaviour among 12,000 respondents in 7 countries indicates that high risk perceptions do not necessarily result in improved mitigation behaviour, as is often suggested. The survey shows that flood-coping appraisals are also important variables of influence on four different types of flood mitigation behaviour. Both response-efficacy and self-efficacy are found to considerably influence flood mitigation behaviour. Moreover, it is shown that, in addition to flood experience, the level of income plays an important role as far as the implementation of expensive structural measures is concerned. Besides, the social environment and non-protective responses are of significant influence on different types of flood mitigation behaviour.

1. Introduction

The Rhine basin is a densely populated river basin and economically the most important river in Western Europe. Currently, more than 10 million people are living in areas at risk of flooding events, especially in the upstream German area of the river Rhine (ICPR, 2001). Flood risk is expected to increase due to the effects of climate change and socio-economic development in flood-prone areas. Flood management in Europe and in the Rhine has increasingly shifted to integrated risk management approaches, including measures that reduce damage and exposure (de Moel et al. 2009; Büchele et al. 2006). The EU flood directive, which requires member states to develop flood management plans on the basis of flood risk assessments, added further impetus to this trend in Europe (Commission of the European 2006). Nowadays, the contribution of private households to damage reduction by means private flood mitigation measures has become an important component of integrated flood risk management strategies in many countries (Bubeck et al. 2012c). In Germany, for instance, the responsibility of private households to flood damage reduction has been increasingly emphasized and embedded into flood risk management in response to severe floods in 1993 and 1995 along the Rhine and Meuse and in 2002 along the Elbe and Danube (Federal Environment Agency 2010; Bubeck et al. 2012c). Previous studies indicated that precautionary measures at the building level can effectively reduce flood damage and are cost-efficient in many situations (Kreibich et al. 2005; Olfert 2008).

However, despite the growing importance of private flood mitigation measures in contemporary integrated flood risk management, knowledge on them remains scarce. Therefore, this research will develop methods to gain a better understanding of flood risk developments and the effect of various adaptation strategies for reducing these risks, including the role of private flood risk management (ICPR, 2011). Therefore, the research undertaken within the project *Assessment of upstream flood risk in the Rhine Basin (HSGR02)* aimed at developing a uniform flood risk methodology to assess current and future flood risks in both Netherlands and the upstream German and French part of the Rhine basin, and to gain better insights into the potential of possible adaptation strategies, with emphasis on local scale adaptation.

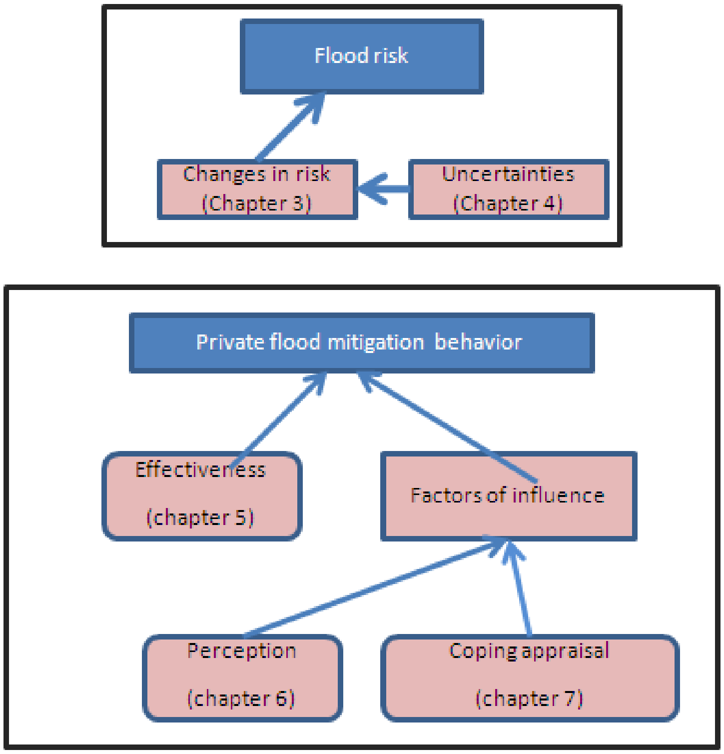

Figure 0. Overview of research elements and their interlinkages

This report summarizes the main findings of the project and provides an overview on its outputs. Chapter 2 introduces the Rhine basin and the geographical characteristics. Chapter 3 presents a scenario study of changes in future flood risk from extreme events along the River Rhine and examines the independent contribution of climate change and socio-economic developments to these developments. The uncertainties stemming from the application of different damage models in such scenario studies are addressed in detail in Chapter 4. The long-term development of flood mitigation measures, their current implementation level among private households along the Rhine and their damage-reducing effect during two consecutive flood events in 1993 and 1995 is assessed in Chapter 5. The relation between flood risk perceptions and mitigation behaviour, as well as a review of a wide range of factors potentially influencing flood mitigation behaviour is provided in a review article in Chapter 6. Chapter 7 provides detailed insights into the influence of the independent components of flood-coping appraisals on four different types of flood mitigation behaviours by flood-prone households along the Rhine. Overall recommendations are provided in Chapter 8, which also discusses the implications of this report's findings for contemporary integrated flood risk management.

2. The Rhine Basin

The river Rhine originates in the Alps in Switzerland, forms part of the boundary between France and Germany and continues flowing through Germany before it enters the Netherlands at Lobith (Figure 1a). The Rhine is one of the most important industrial transport routes in the world and connects one of the largest sea harbours, the port of Rotterdam, to the inland European markets and its large industrial complexes (Jonkeren 2009). About 58 million people inhabit the river basin, of which 10.5 million live in flood-prone areas (ICPR 2001). The average discharge (Over the years 1961-1990) at Lobith in the Lower Rhine is 2200m3 s−1 and the maximum observed discharge was 12 600m3 s^{-1} in 1926 (Pinter et al 2006). Flood innundation depths can reach several metres, also in urban areas (Figure 1b).

Water management has heavily influenced the characteristics of the Rhine. Prior to the 19th century, the Rhine was a multi-channel braided river system upstream of Worms and meandering from that point downstream. However in order to reduce flooding, the Upper Rhine was canalized between 1817 and 1890 (Blackbourn 2006). Furthermore, to aid shipping, engineers further rectified and canalized the main branch until 1955, causing additional acceleration of flood wave propagation in the Rhine (Lammersen et al. 2002).

The basin area is 185,000 km^2 and in particular the flood-prone areas in the basin are densely populated. Hence, flood management has predominantly focused on major dike reinforcements along the Rhine over the last 20–30 years. Safety levels vary from 1/200 to 1/500 per year in Germany to 1/1250 and 1/2000 per year in the Netherlands. The design discharge that is associated with a safety level of 1/1250 per year (the discharge used when designing flood defences) is estimated at 16000 m^3 s^{-1} (Ministry of Transport, Public Works and Water Management 2006, Figure 1a). Due to lower safety levels in Germany, floods may occur at upstream sections in Germany while the Dutch dike system will still prevent huge areas from inundation downstream (Gudden 2004; Apel et al. 2006).

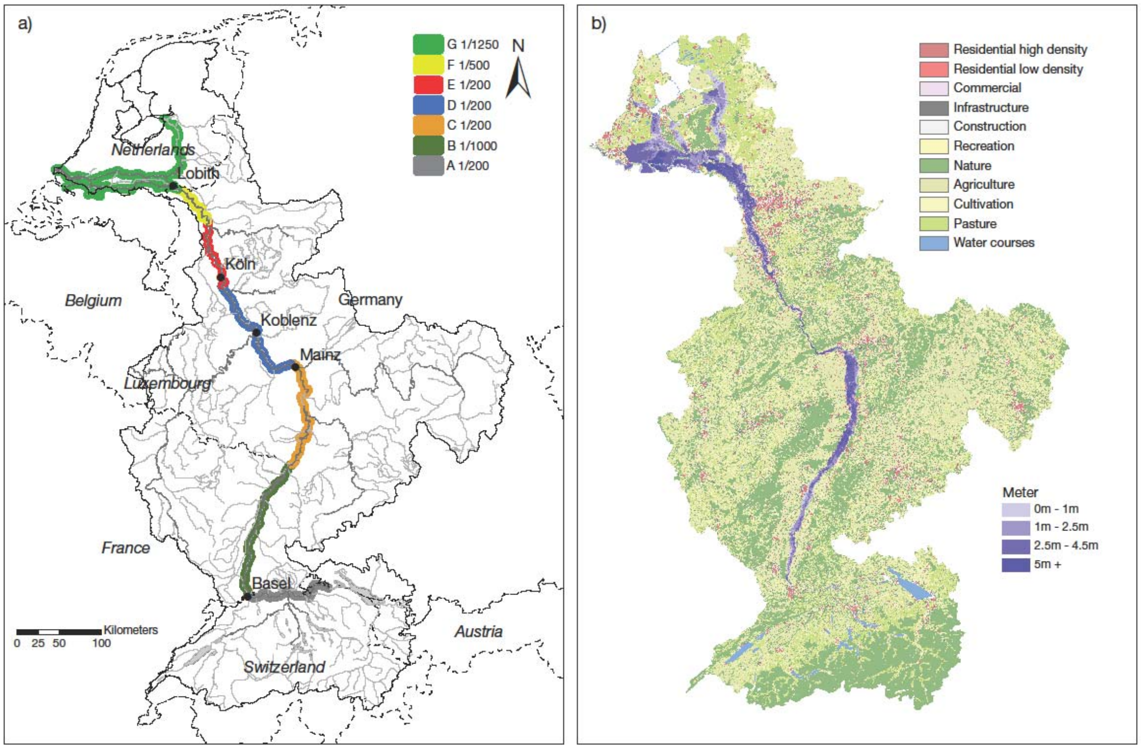

Figure 1: Maps of the Rhine basin: (a) (estimated) safety levels and (b) land use in the reference situation. Figure (b) also shows the potentially inundated area due to fluvial flooding from the Rhine.

3. Future flood risk estimates along the River Rhine[1]

The impact of flood events on societies and economies in the Rhine basin is can increase further as a result of two complementary trends. First of all, climate change is expected to increase the frequency and magnitude of flood peaks in the Rhine basin (Hooijer et al. 2004; Pinter et al. 2006). Annual maximum peak discharges are expected to increase by 3–19% in 2050 due to climate change (Kwadijk 1993; Middelkoop et al. 2001; Vellinga et al. 2001). Te Linde et al. (2010) estimate an increase in the occurrence of an extreme 1/1250 per year flood event in the Lower Rhine delta by a factor of three to five in 2050. Secondly, the economic impact of natural catastrophes is increasing due to the growing number of people living in areas with a high flood exposure level, as well as the increased economic activity in these regions (e.g. Bouwer et al. 2007; Pielke Jr. et al. 2008).

In this Chapter we estimate current and future flood risk for the entire Rhine basin in a scenario study. For this, we first assessed changes in flood probability at various locations along the Rhine using climate scenarios and hydrological models. Second, we developed a land-use simulation model for the Rhine basin to generate future changes in land use. Third, these future land-use maps were used to estimate potential flood damage in flood-prone areas using a damage model. Finally, we multiplied flood probabilities with flood damage to derive current and future flood risk for the Rhine basin (Figure 2).

We used a simple damage model for land use categories, the Damage Scanner (Aerts et al. 2008; Bouwer et al. 2010; Klijn et al. 2007). This model is based on two input parameters: water depth and land use. Potential damage is calculated by the model using so-called damage functions that define for a land-use category the damage that can be expected when a respective inundation level occurs. The model applies damage functions for the 13 land-use classes distinguished by the Land Use Scanner and reflects predominantly direct tangible damage caused by physical contact between economic assets and flood water. More information on vulnerable assets cab be derived from the Basic European Asset Map (BEAM). The BEAM product displays monetary values per area unit (e.g €/m²) on country level. Up-to-date national available land use data sets – supplemented by street network data – and socio-economic statistics available via eurostat serve as input data to relatively quickly

[1] This section is based on A.H. te Linde, P. Bubeck, J.E.C. Deckers, H. de Moel and J.C.J.H. Aerts, (2011). Future flood risk estimates along the river Rhine. Natural Hazards and Earth System Sciences, 11, 459-473.

produce this map (http://www.geomer.de/fileadmin/templates/main/res/downloads/BEAM-manual_v14.pdf).

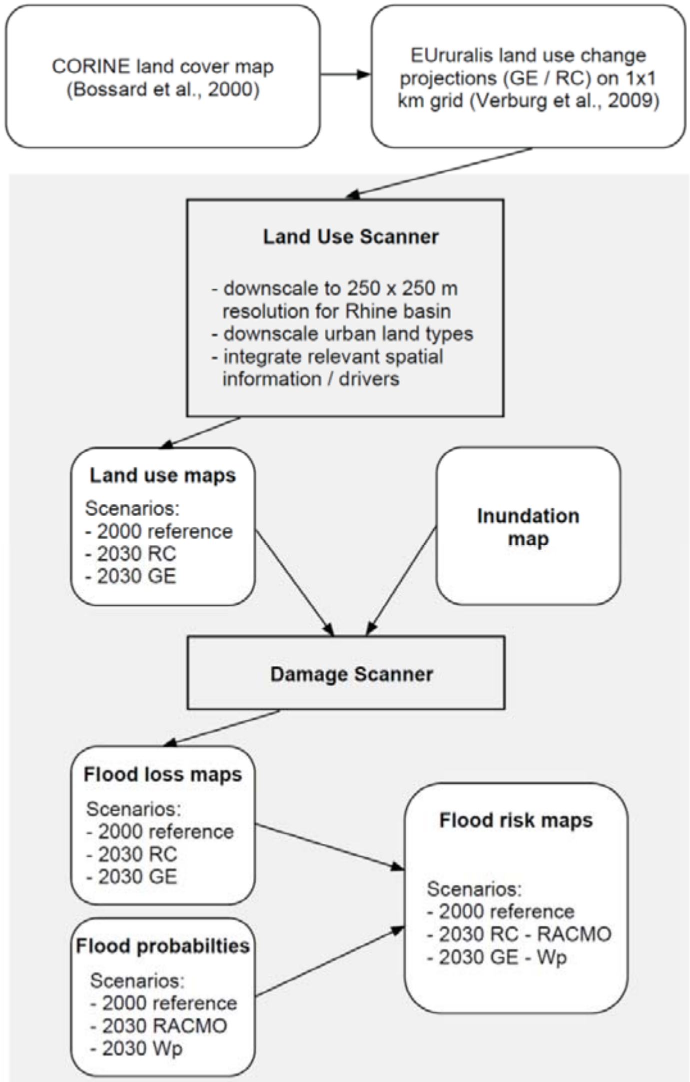

Figure 2: Flowchart of the method used for estimating future flood risk

Figure 1a shows current safety levels for seven regions along the main Rhine branch. In the Netherlands, there is a legal standard for flood defense safety levels. In Germany, dike heights are often legally defined and the related safety levels are estimated and described by ICPR (2005) and Silva and Van Velzen (2008). The differences in safety levels were used to distinguish the regions for which aggregated flood damage and flood risk can be calculated. We assumed flooding occurs at probabilities corresponding to the safety levels in the reference situation.

We used two climate change scenarios (a moderate (Wp) and an extreme (RACMO) scenario) to estimate future changes in flood probabilities along the main Rhine branch, which were taken from Te Linde et al. (2010).

Figure 3 shows an extreme value plot for annual maximum discharges at Lobith, for the year 1990 and two climate change scenarios for 2050. The results represent 1000-year runs for the reference and each climate change scenario (Wp and RACMO). From the simulation results it can be derived that the discharge corresponding to a probability of 1/1250 per year at Lobith increases by 16% for the Wp scenario and by 13% for the RACMO scenario. The discharge currently corresponding to the 1/1250 event (about 16 000m^3 s^{-1}) will increase to 1/460 per year for the RACMO scenario and 1/265 per year for the Wp scenario, meaning the probability increases by a factor of 2.7 to 4.7, respectively (Te Linde et al., 2010). Similar projected changes in flood probabilities are available for several locations along the Rhine branch, representing the regions A through G in Figure 1 with different safety levels. The projected increases in flood probabilities for 2030 range from a factor of 1.3 to 3.8, depending on region and climate change scenario (Table 1).

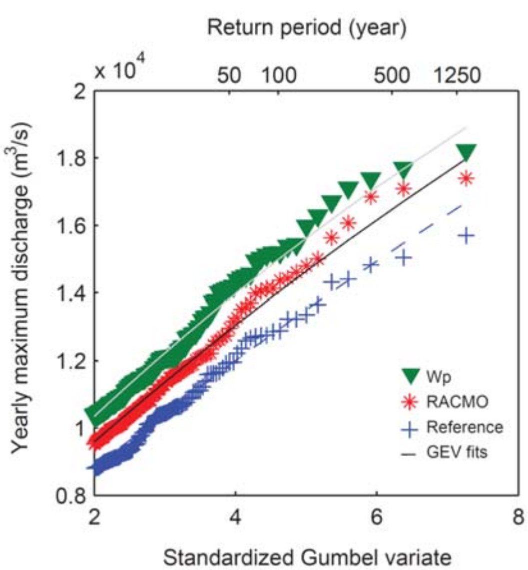

Figure 3: Extreme value distributions of annual maximum discharge at Lobith, and Generalized Extreme Value (GEV) fits (lines) for the reference situation, and the RACMO and Wp climate change scenarios for the year 2050 (adapted from Te Linde et al. 2010).

Table 1: Climate change scenarios for increased flooding probabilities in 2030. Flooding probabilities (per year) for the reference situation are estimated based on literature. The probability (p) increase is displayed as a factor (* estimate, based on Silva and Van Velzen (2008) and on the Evaluation of the Action Plan on Floods (ICPR 2005))

	Reference*	RACMO	Wp	RACMO	Wp
Region		*p*	*p*	*p increase*	
Alpine A	1/200 (0.0050)	1/139 (0.0072)	1/64 (0.0157)	1.4	3.1
Upper Rhine B	1/1000 (0.0010)	1/691 (0.0014)	1/261 (0.0038)	1.5	3.9
Upper Rhine C	1/200 (0.0050)	1/160 (0.0062)	1/77 (0.0129)	1.3	2.6
Middle Rhine D	1/200 (0.0050)	1/159 (0.0063)	1/80 (0.0125)	1.3	2.5
Lower Rhine E	1/200 (0.0050)	1/134 (0.0075)	1/80 (0.0125)	1.5	2.5
Lower Rhine F	1/500 (0.0020)	1/327 (0.0031)	1/162 (0.0062)	1.5	3.1
Delta G	1/1250 (0.0008)	1/673 (0.0015)	1/437 (0.0023)	1.9	2.9
	1/2000 (0.0005)	1/1080 (0.0009)	1/702 (0.0014)		

Figure 4a display the expected damage aggregated for the seven regions along the Rhine. For the reference year (2000), we estimated the total potential damage for the whole basin to be Eur 300 billion. The expected damage gradually increases downstream. The delta in the Netherlands (region G) is the largest and most densely populated region, and has therefore the highest potential damage, both in the reference situation as well as in the future projections of both socio-economic scenarios. Between the two scenarios, the RC scenario yields the lowest increase in potential damage: 7.5% over the entire basin. In most regions potential damage changes little, with the exception of the Lower Rhine region (F) (+18%). In some areas, such as the Middle Rhine, the RC scenario even projects a decrease in potential damage. The GE scenario gives an overall larger increase in potential damage (21%). Moreover, expected damage seems to increase substantially in almost all regions, often by more than 15% and ranging up to 34%.

Figure 4b shows estimates of expected annual flood damage in the reference year (2000) for the seven regions along the Rhine. In contrast with potential damage (Figure 5a), the highest flood risk estimates are not found in the Dutch Delta (G), but rather in the Lower Rhine (E) in the German state Nordrhein-Westfalen and in the Upper Rhine (C). This is the result of the substantially higher flood protection levels in the Delta region G, which obviously determines and lowers the flood-risk estimates to a large extent. This also implies that uncertainties of flood probabilities heavily affect the reliability of (future) flood-risk estimates in this region.

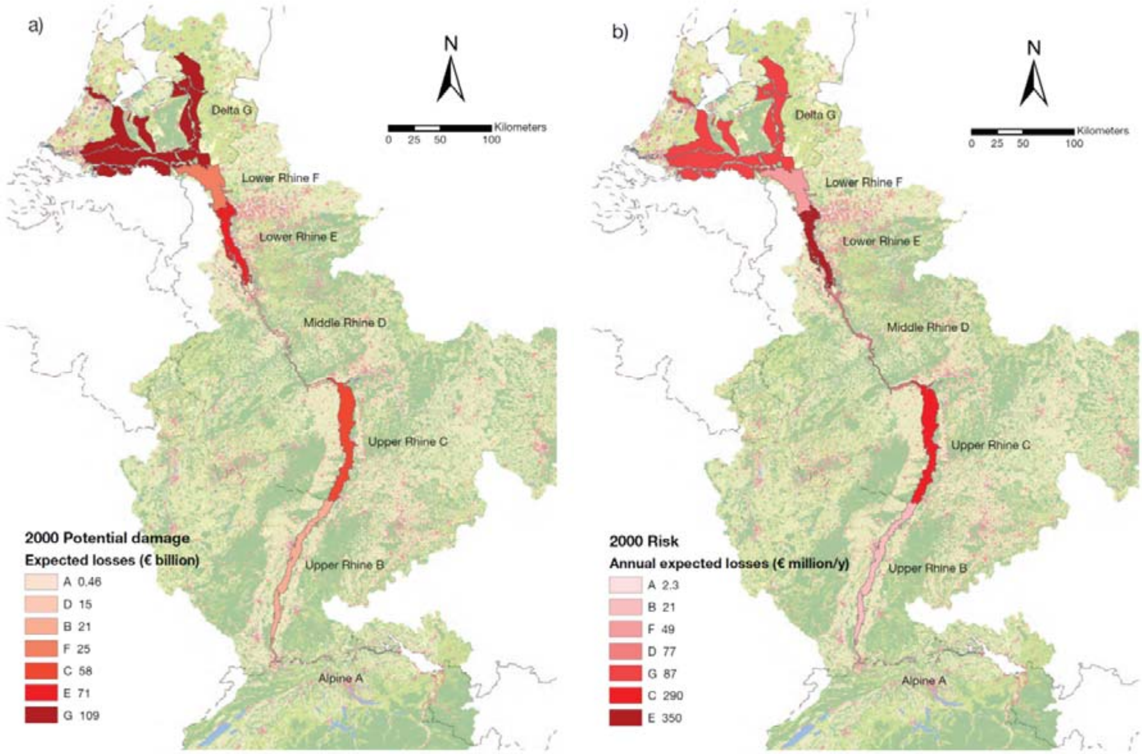

Figure 4: Potential damage (a) and flood risk (b), aggregated to seven regions along the Rhine

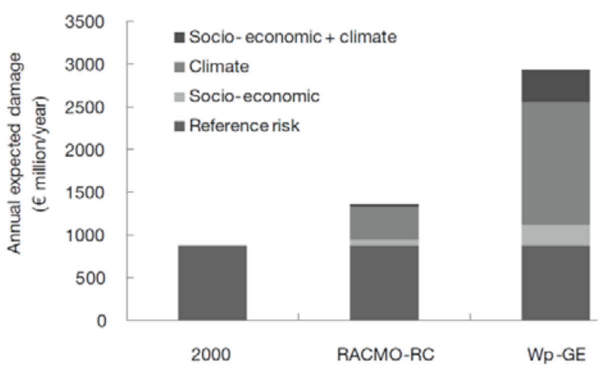

Figure 5: Basin-wide annual expected flood damage (risk) for 2030, compared to the reference situation

Table 2: Basin-wide annual expected damage (risk) in Eur million per year. The factor of change is displayed in brackets. The reference year is 2000 and the scenarios represent 2030

		Socio-economic scenario		
		Reference	RC	GE
[illegible]	Reference	880	950 (7.5%)	1100 (27%)

RACMO	1300 (43%)	1400 (54%)	1600 (81%)
Wp	2300 (160%)	2500 (180%)	2900 (230%)

For the future risk projections, the RACMO climate scenario is combined with the RC socio-economic scenario and Wp with the GE scenario. The combination RACMO-RC can be considered as the lower estimate and Wp-GE as the upper estimate in the risk simulations. Basin-wide results are displayed in Table 2. The flood risk estimates of the scenarios show a large variation. In the reference situation, we estimate the basin-wide expected annual flood damage to be Eur 880 million on average per year. The RACMO-RC scenario projects the risk to increase to Eur 1400 million per year, an increase of 54%. The Wp-GE scenario projects a much larger increase in flood risk, tripling it to Eur 2900 million per year (an increase of 230%).

The contribution made by climate change is considerably larger than socio-economic change in both scenario combinations. Due to climate change, basin-wide flood risk increases by 43-160%, whereas land-use change results in an increase of 7.5-27% (Table 2). In order to illustrate the relative increase of annual expected damage due to each of the driving forces, we displayed the basin-wide flood risk scenarios in a bar chart (Figure 5). The bar chart displays the contributions to change in annual expected damage, from (a) climate change only, (b) socio-economic change only, and (c) the combination of both impacts. Climate change accounts for ~three-quarters (6/8) of the increase, whereas socioeconomic change only results in ~1/8 of the total increase in annual expected damage. The combination of impacts adds the remaining ~1/8 to both scenarios, respectively.

As this is the first assessment of basin-wide future flood risk, it is interesting to compare different sections along the Rhine and to evaluate if differences with regard to the drivers of future flood risk can be observed. To assess differences between regions along the Rhine, bar charts similar to Figure 5 are shown in Figure 6, but now disaggregated to seven regions along the Rhine. The bar charts show large variations in base risk and flood risk projections between regions, and, like the basin-wide projections, the dominant contribution of climate change to increased flood risk.

It can be concluded that, in absolute terms, potential flood damage is highest in the Dutch Delta region (G), namely Eur 110 billion, compared to Eur 71 billion of the second highest value in the Lower Rhine region (E). Flood risk (damage × probability) is, on the other hand, much higher in other regions, most notably in the Lower Rhine region E (Eur 350 million per year) and the Upper Rhine C (Eur 290 million per year), whereas the Dutch Delta region (G) only reaches Eur 87 million per year.

Our research further projected that flood risk in the Rhine basin will not be stationary and might considerably increase over a period of several decades. Expected annual damage in the entire Rhine basin may increase by between 54% and 230%, due to socio-economic and climate change. The results display large variations in current risk and flood risk projections between regions along the Rhine. The increase in flood risk can mainly be attributed to increasing probabilities of flood peaks due to climate change (43-160%, which is ~6/8 of the total risk increase), whereas socioeconomic change accounts for 7.5-27% increase, which is ~1/8 of the total risk increase.

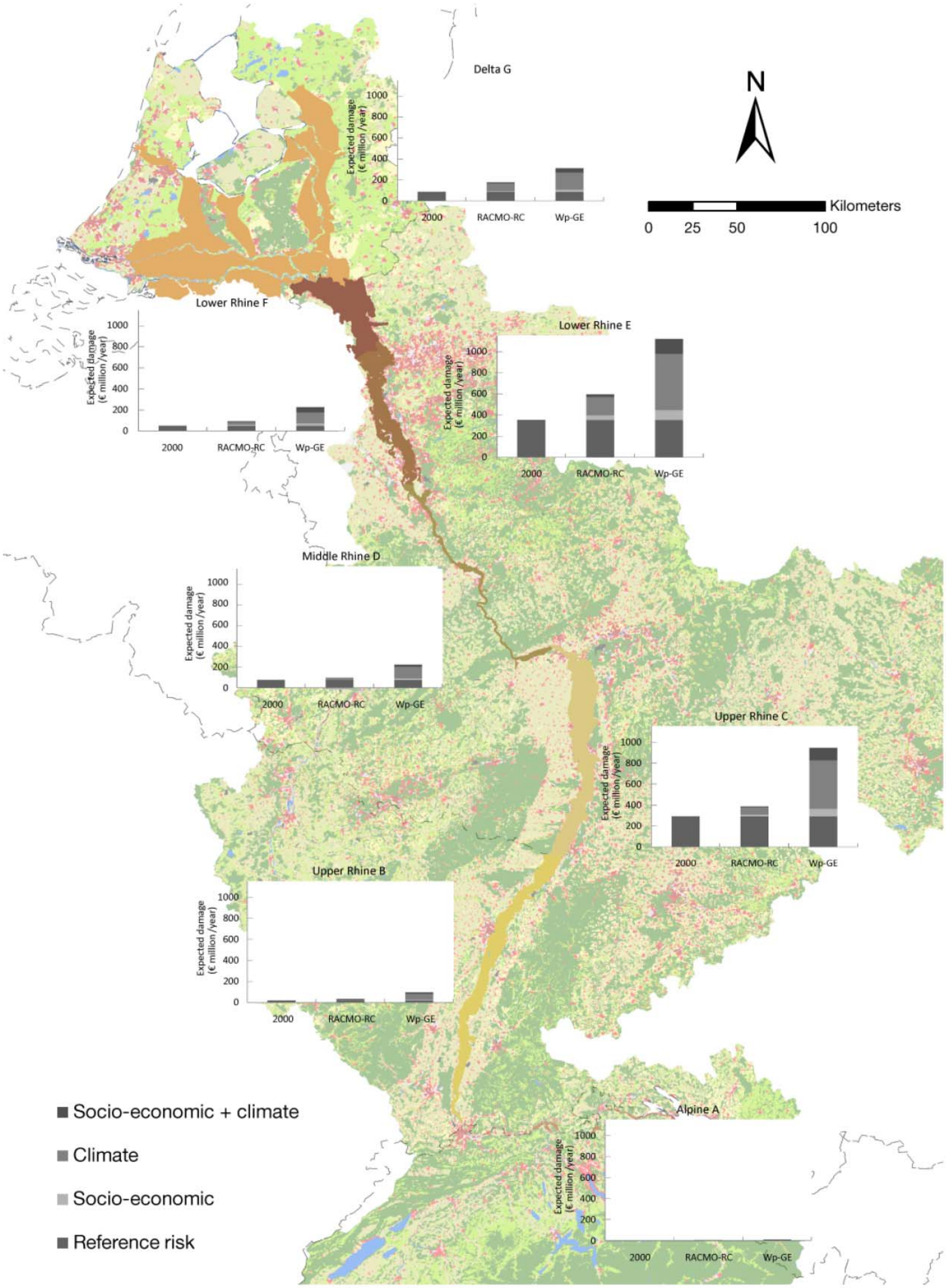

Figure 6: Annual expected flood damage, for the reference situation and projections for 2030, aggregated into seven regions along the Rhine

Our method provides a more comprehensive assessment of basin-wide flood risk in the Rhine than was previously possible as existing studies either assessed flood risk in the Netherlands or in upstream areas in Germany (Apel et al. 2004; Klijn et al. 2007; Aerts et al. 2008; Bouwer et al. 2010). Furthermore, our method enables basin-wide scenario projections for future land use and potential damage, by integrating a land-use model with a damage model at a high spatial resolution.

Finally, the implementation of flood defense measures, such as retention basins and dike heightening, might prevent the increase in flood probability due to climate change, and thus the contribution of climate change to flood risk. This requires a thorough analysis of the effectiveness of flood management measures under different climate change scenarios. Spatial planning policies and damage mitigation measures and risk transfer mechanisms, such as flood proofing of buildings and insurance, might further reduce flood risk. Such flood risk decisions may have implications for several decades. Therefore, flood risk management needs to deal with expected climate and socio-economic changes (Merz et al. 2010).

4. Uncertainties of flood damage projections resulting from the application of different flood damage models[2]

In recent years, flood management throughout Europe has gradually shifted from what are called 'flood control approaches' to more integrated concepts, referred to as 'flood risk management'. While flood control approaches predominantly focused on preventing flood events with specific pre-defined return periods, flood risk management also takes into account the expected consequences of flooding, such as direct economic losses or loss of life (Büchele et al. 2006; De Moel et al. 2009; Merz et al. 2010). Risk in this context is defined as 'probability times damage', and thus describes the expected damage that can occur or will be exceeded with a certain probability in a certain period (e.g. Merz et al. 2010).

Following this shift to risk-based approaches, there has been an increasing interest in flood impact assessment and especially the estimation of direct economic losses (Dutta et al 2003; Merz et al. 2004; Hall et al. 2005; Penning-Roswell et al. 2005; Thieken et al. 2005; Bouwer et al. 2009; Luino et al. 2009; Kreibich et al. 2010). Knowledge of potential flood damage has a great importance for, inter alia, the identification of people and assets at risk, the planning and evaluation of effective flood mitigation and control measures, the creation of flood risk maps for awareness raising, and the calculation of flood insurance premiums (Messner et al. 2007; Merz et al. 2010). Furthermore, flood damage is projected to increase in the coming decades owing to on-going development in flood-prone areas and the projected effects of climate change on river discharges, and consequently flood probabilities (Middelkoop et al. 2001; IPCC 2007; Te Linde et al. 2010). Against this background, a growing number of studies have estimated the range of possible changes in the development of future flood damage in Europe (Hall et al. 2005; Aerts et al. 2008; ABI 2009; Feyen et al. 2009; maaskant et al. 2009; Bouwer et al. 2010; Te Linde et al. 2011).

Generally, flood damage assessments are still characterized by significant uncertainties associated with stage-damage functions, as well as methodological differences in estimating the exposed asset values linked to these curves (Merz et al. 2004; Apel et al. 2008; Apel et al. 2009; Frene et al. 2010; Merze et al. 2010; De Moel and Aerts 2011).

In order to better manage the large variations that are commonly associated with assessments of absolute flood damage, it is suggested that it would be useful to investigate the reliability of

[2] This section is based on P. Bubeck, H. de Moel, L.M. Bouwer and J.C.J.H. Aerts, (2011) How reliable are projections of future flood damage?, Natural Hazards and Earth System Sciences, 11, 3293-3306.

estimates of relative changes in the development of potential flood damage, in terms of the differences stemming from flood damage modelling approaches (De Moel and Aerts 2011). Gaining insights into the reliability of relative estimates (as the percentage change of a reference situation) of flood damage in scenario studies is important, as these often form the basis of decision making and are used, for example, to evaluate the effectiveness of various risk reducing-strategies (ICPR 2006; Aerts et al. 2008; ABI 2009; Bouwer et al. 2010). The latter purpose is especially important, because many investments in flood control and mitigation measures take 20 to 30 years to design, plan and implement and are also designed for long life spans (see e.g. Hallegatte 2009; Dircke et al. 2010).

To examine the uncertainties of flood damage projections resulting from the application of different flood damage models, we calculated potential flood damage along the River Rhine for the period from 1990 to 2030, using two damage models commonly applied in the Rhine basin (Figure 7): namely, the Damage Scanner model and the damage model that was used for the development of the Rhine Atlas (ICPR, 2001).

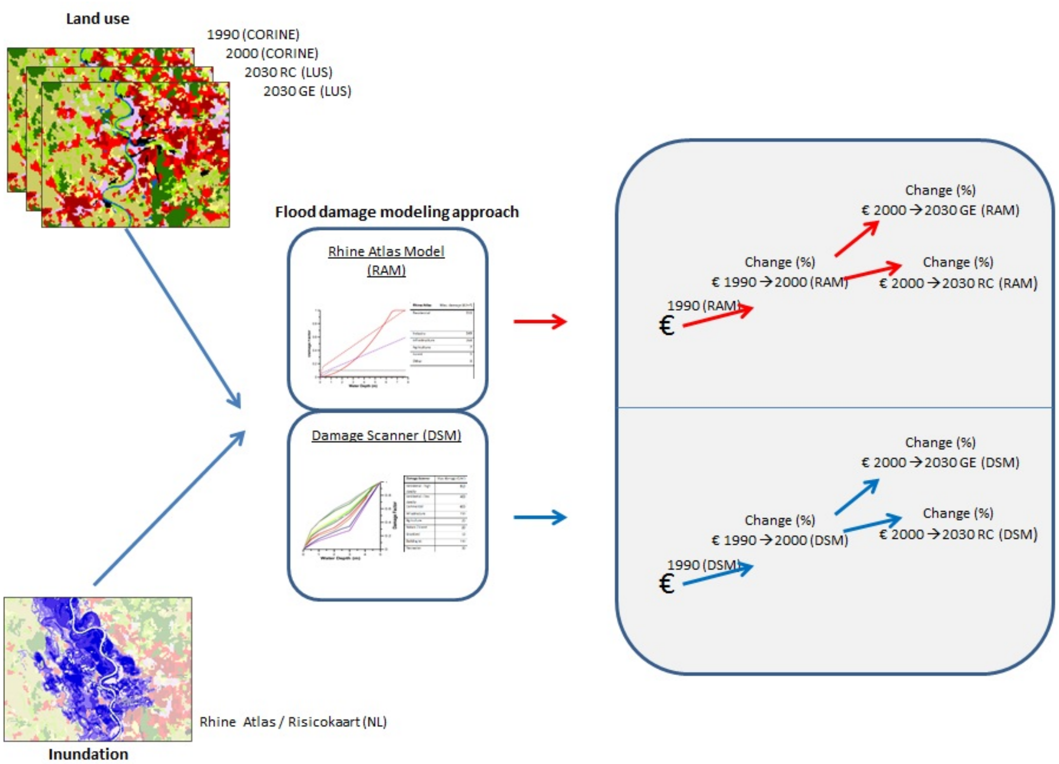

Figure 7: Flow chart of the input data and method applied to evaluate the reliability of relative estimates of flood damage developments

The comparison shows that the application of the different damage models results in large differences in terms of absolute damage values (by a factor 3.5 to 3.8 for the different time steps) (Table 3). These variations can be attributed to both the difference in the underlying asset values and differences in the applied damage curves (data not shown).

Table 3: Potential flood damage along the Rhine (Million €) for different time-steps, according to the Rhine Atlas and the Damage Scanner damage model

	1990	2000	2030 RC	2030 GE
Rhine Atlas model	74,591	77,749	86,982	108,158
Damage Scanner model	290,883	300,463	323,608	380,684
Difference factor between models	3.8	3.8	3.7	3.5

The large differences in absolute damage estimates that result from the application of the two different damage modelling approaches is the reason for evaluating the reliability of relative estimates. We therefore assess the results from the two models in terms of relative changes in potential flood damage for the periods 1990 to 2000 and 2000 to 2030. The comparison in terms of estimates of relative changes reveals that the variation between the two models is considerably smaller (by a factor of about 1.4), compared with differences observed for the absolute damage estimates of the two models (Table 4). The difference in terms of estimates of relative changes in the development of flood damage between the two models can be predominantly attributed to differences in the applied damage curves (data not shown).

Table 4: Relative estimate of damage developments of the model-run Rapid Assessment Model (RAM), Damage Scanner Model (DSM) ^{DSM} and difference factors between relative estimates of the RAM and the RAM^{DSM}, and between the RAM^{DSM} and the DSM

	1990-2000	2000 - RC	2000-GE
RAM^{DSM}	4.16%	11.96%	38.85%
Diff. due to max. damage values*	0.99	1.01	0.99
Diff. due to function**	1.15	1.41	1.42

* RAM^{DSM} to RAM (difference factor).
**RAM^{DSM} to DSM (difference factor).

These findings provide valuable insights for intergovernmental river-basin organizations like the International Commission for the Protection of the Rhine (ICPR). Such organizations are increasingly required to engage in trans-boundary flood risk assessments under the EU Water Framework Directive, and usually need to choose among various flood damage modelling approaches when doing so.

In order to improve the reliability of relative estimates of flood damage developments, future research should focus on reducing the uncertainties of stage-damage functions, which originates from the huge variability of observed damage even among similar elements at risk. Although it is only possible to integrate this enormous variability in flood damage modelling approaches to a limited extent, it has been shown that model performance can be improved by integrating several damage-influencing parameters in multi-parameter damage modelling (e.g. Elmer et al. 2010). As this requires detailed data on damage processes at the level of individual objects, data collection after flood events remains a crucial activity.

5. Use and effectiveness of private flood mitigation measures along the River Rhine[3]

In line with a general trend towards more integrated flood risk management approaches, the contribution of private households to flood damage reduction gained increasing importance in Germany, as well as on a European and global level (ICPR 2002; Few 2003; Federal Environment Agency 2010; Bubeck et al. 2012). Complementary to traditional flood protection, such integrated approaches also aim at reducing the potential consequences of floods, amongst others, by means of private flood mitigation measures, such as flood-adapted building use or the deployment of flood barriers. Previous research indicated that these measures are effective in reducing damage and are cost-efficient in many situations (Kreibich et al. 2005; Olfert 2008; Kreibich et al. 2011).

However, even though private flood mitigation measures have become an integral component of contemporary flood risk management in Germany and many other countries, knowledge about the latter is still scarce. In particular, the long-term development and the current implementation level of mitigation measures among flood-prone households, as well as their damage reducing effect are only sporadically known, and, such knowledge is often confined to specific regions (e.g. Thieken et al. 2007). For instance, the current implementation level and effectiveness of private flood mitigation measures along the Rhine, which is Europe's largest and economically most important river in Western Europe, has, so far, only been estimated on the basis of expert judgement without a solid empirical basis (ICPR 2002).

To arrive at a better understanding of the long-term development of the implementation of flood mitigation measures, and their risk-reducing effect, empirical data from a computer-aided telephone survey among 752 flood-prone households along the German part of the River Rhine were analysed. The damage reducing effect of private flood mitigation measures will be examined by comparing the precautionary behaviour and damage suffered of households that were affected by two major floods in 1993 and 1995 along the Rhine. Such a comparison is of interest, because the hazard characteristics of both flood events were of a comparable magnitude (Engel 1997). Nevertheless, aggregated damage reported for the 1995 event along the Rhine was substantially lower than in 1993 and it has been repeatedly suggested that this was also due to an improved preparedness of the population affected by the

[3] This section is based on P. Bubeck, W.J.W. Botzen, H. Kreibich and J.C.J.H. Aerts (2012) Long-term development and effectiveness of private flood mitigation measures: An analysis for the German part of the river Rhine. *Natural Hazards and Earth System Sciences*, under review.

floods (e.g. Engel 1997; Kron and Thumerer 2002). However, it has not been estimated on a household level, yet, whether the difference in damage between the two flood events can indeed be attributed to improved mitigation behaviour.

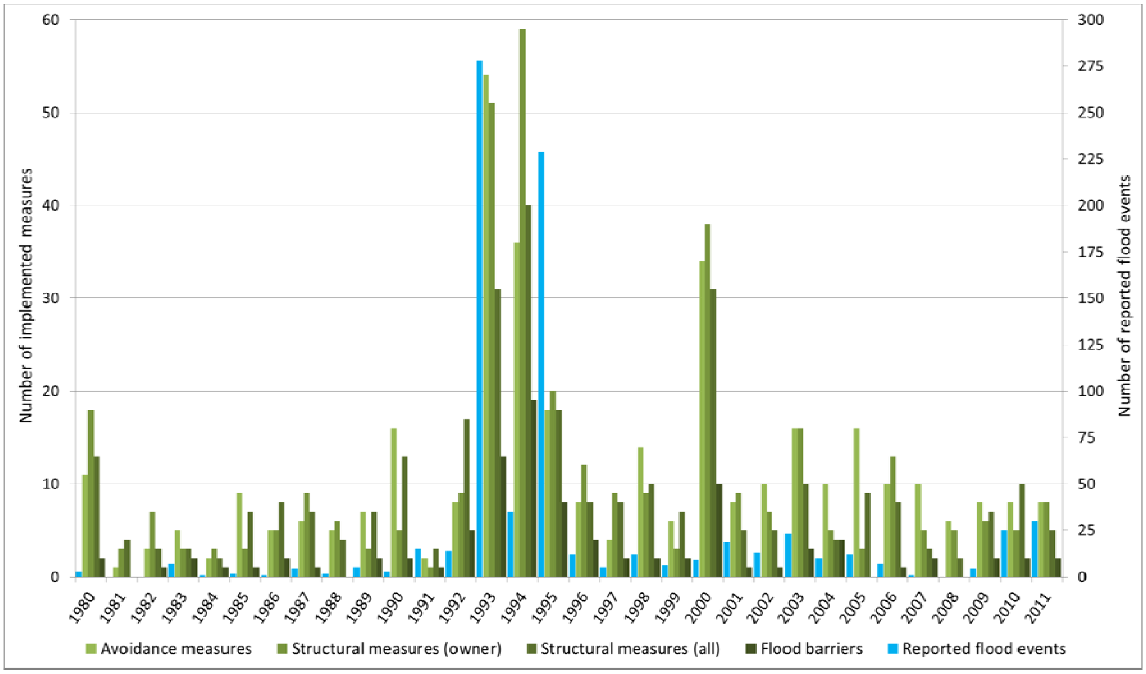

Figure 8: Long-term development of the implementation of four types of flood mitigation measures by flood-prone households (n=752) along the German part of the Rhine.

Figure 8 provides an overview on the flood events reported as most severe by the respondents as well as the long-term development of four different types of flood mitigation measures among flood-prone households between 1980 and 2011: namely, structural measures implemented by homeowners, structural measures implemented by owners and tenants, avoidance measures and flood barriers. Figure 8 clearly indicates that the 1993 and 1995 events have been the dominant flood events experienced by the surveyed households. While 278 respondents indicated that the 1993 flood belonged to the two most severe flood events they had experienced, 229 respondents did so for the 1995 flood. In terms of implemented flood mitigation measures, Figure 8 shows that all four types were deployed gradually over time, with major flood events being important triggers for an accelerated implementation. Especially in the aftermath of the severe floods in 1993, a remarkable increase in the number of undertaken measures can be observed for all four types. That flood experience strongly influences the adoption of precautionary measures is also confirmed by correlation analyses. The number reported flood events per year shows a strong correlation with the number of implemented measures (Cohen 1994). The correlation coefficients range from r = 0.52 for structural measures up to r = 0.67 for avoidance measures.

A detailed picture of the current implementation level of various flood mitigation measures split by tenants (n=295) and homeowners (n=457) is provided in Table 5. As can be seen from Table 5, flood mitigation measures are frequently deployed by those at high risk of flooding, especially by homeowners. 56 per cent of the homeowners and 36 per cent of the tenants implemented at least one flood-mitigation measure. Measures that are particularly popular among the households at risk are avoidance measures as well as structural measures, while the deployment of flood barriers is less common (Table 5).

Table 5: Current implementation level of various flood mitigation measures among private households along the Rhine (n=752).

Type of flood mitigation measure	Owners (%)	Tenants (%)
Relocate heating system to avoid contamination	33	n.a.*
Replace oil heating system to avoid contamination	24	n.a.*
Improve building stability	24	n.a.*
Use of flood resistant materials	22	n.a.*
Secure oil tank to prevent contamination	8	6
Install a back flow protection system	31	17
Avoid expensive fixed interior in flood-prone storeys	30	22
Avoid expensive items in flood-prone storeys	36	29
Deploy fixed or mobile flood barriers	19	13
Purchase a flood insurance policy	28	18
At least one measure implemented	56	36

*Note: str.= structural measure, avoid.= avoidance measure, barr.=flood barrier.
*Note: n.a. stands for not applicable. This type of measure was elicited for homeowners only, because it can usually not be carried out by tenants

A comparison of damage to households (building structure and household contents) during the flood events in 1993 and 1995, which had very similar hazard characteristics and inundations levels, showed that damage in 1995 was substantially lower due to in improved preparedness of the population (Figure 9).

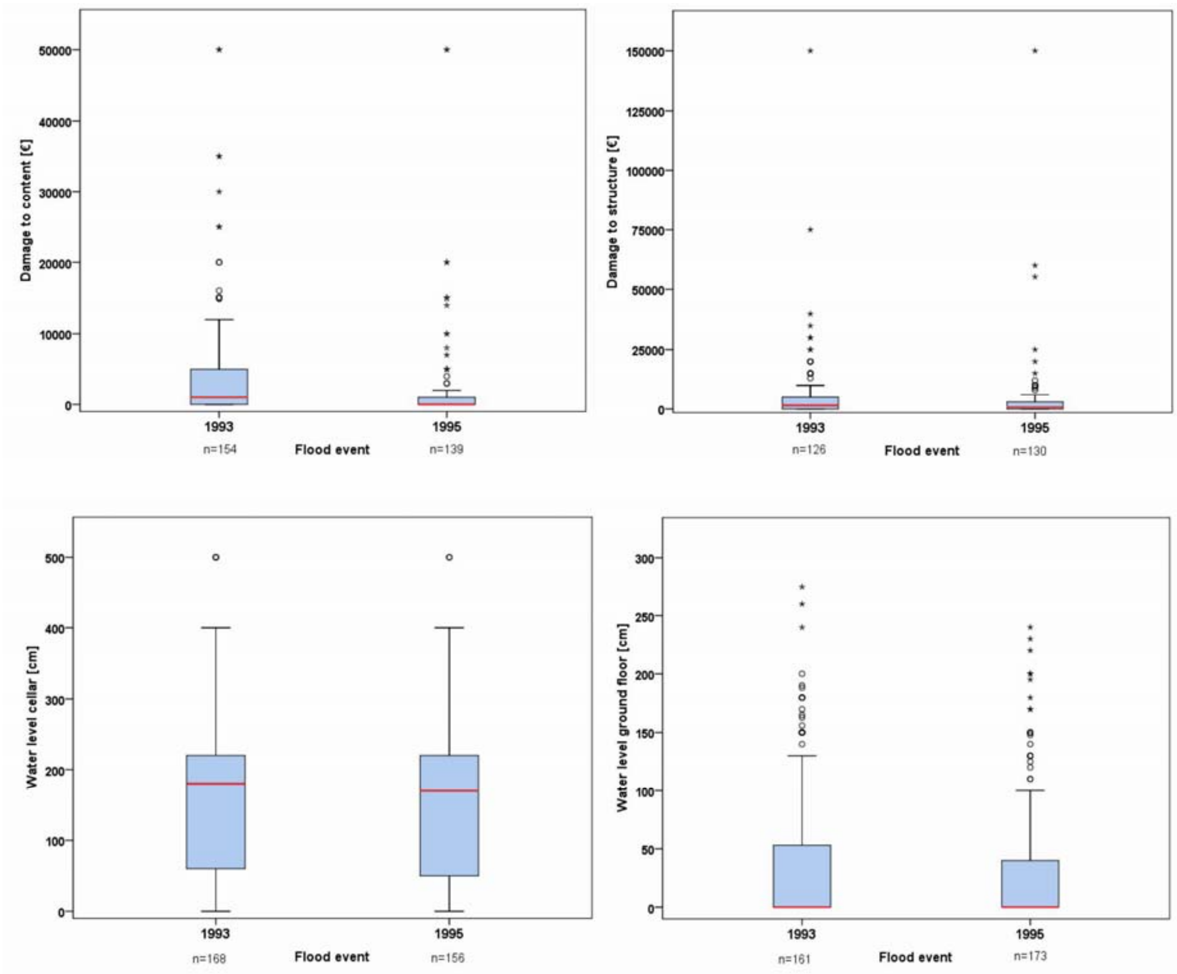

Figure 9: Box-whisker plots of damage to contents (a), damage to structure (b), the water level in the cellar (c), and the water level in the ground floor (d). Note: Damage to contents, damage to structure, water levels in cellar and ground floor are significantly different (Wilcoxon signed-rank test) at the 1 per cent level.

Further analyses confirmed that the improved preparedness of the population resulted in lower flood damage. Respondents who increased their level of preparedness between the two flood events in 1993 and 1995 showed the largest reduction while this effect was considerably smaller for other households (Table 6).

Table 6: Damage-reducing effect of flood mitigation measures for respondents with different flood mitigation behaviour.

Types of mitigation behaviour	Damage-reducing effect (r-value)	
	Contents	Structures
(a) No measures in '93 and '95	-0.31** (n=59)	-0.26* (n=65)
(b) No increase in measures	-0.38* (n=33)	n.s. (n=30)
(c) Measure in '93 and increase in '95	-0.43* (n=13)	n.s. (n=11)
(d) Overall increase in measures between '93 and '95	-0.44*** (n=32)	-0.30* (n=28)
(e) No measure in '93 / Measure(s) in '95	-0.46* (n=19)	-0.5* (n=17)

The finding that also the groups without an increase in precaution suffered lower damage in 1995 indicates that other factors than self-protection contributed to lower damage in 1995. It can be assumed that a learning effect also occurred at governmental authorities resulting in a better catastrophe management, as it has been observed in other contexts (Kreibich and Thieken 2009). An additional known factor that led to an overall reduction in damage in 1995 was the significantly lower contamination of flood waters, which again relates to the precautionary behaviour of flood-prone households. Contamination of flood water leads to considerably higher flood damage (Kreibich et al. 2011), and, among several sources of contamination the highest damage increase was being observed for oil contamination(Thieken 2005). Contents and structures affected be oil-contaminated waters often need to be replaced or costly renovated in the aftermath of a flood, instead of simply being cleaned-up. The ICPR (2002) reports for a community at the Danube for a flood in 1999, that 70 per cent of overall flood damage to buildings were caused by oil contamination. Along the Rhine, many households and businesses had replaced their oil- with gas heating, or, had secured their oil tank to avoid contamination in the aftermath of the 1993 event. In the present sample, the number of households who had replaced the oil heating increased from 20 to 47, and, 20 more households had secured their oil tank in 1995. As a consequence, the number of oil spills was drastically lower in 1995. In Cologne, for instance, the number of oil spills dropped from 100 in 1993 to 6 in 1995[4]. This explains that also households that undertook no flood mitigation measures themselves during both events, or, did not increase the level of preparedness, still benefitted from the improved preparedness of others.

Our findings have important implications for contemporary integrated flood risk management. According to the projected effects of climate change, floods will become more frequent and more extreme in several regions and also along the Rhine in the coming decades (Te Linde et

[4] http://undine.bafg.de/servlet/is/13880/

al., 2010). This could imply that floods will increasingly affect areas with little prior flood experience. Given our findings that actual flood experience strongly influences the implementation level of mitigation measures, this also implies that highly vulnerable areas will be affected. Therefore, if flood mitigation measures are indeed to provide an important contribution to contemporary integrated flood risk management, further efforts are required to reach a higher level of implementation among households at risk of flooding. To reach the required level of preparedness also in areas with little prior flood experiences, stricter legal regulations seem unavoidable. These regulations should not only apply to current flood zones (e.g. the 1/ 100 year flood zone) but should anticipate the effects of climate change on these flood zones. That it can be a rewarding undertaking to increase the level of flood mitigation measures at the household level is demonstrated by our finding that an adequate preparedness by private households can considerable contribute to damage reduction.

6. The influence of risk perceptions and other factors on flood mitigation behaviour[5]

Given the growing importance of private flood mitigation in current and future flood risk management, there has been an increased interest in individuals' flood risk perceptions (Baan and Klijn 2004; Siegrist and Gutscher 2006; Plapp and Werner 2006; Terpstra et al. 2009; Botzen et al. 2009a; Plattner et al. 2006), because they are thought to provide important insights for risk management and risk communication strategies. A main reason for this is their expected positive relationship with the willingness of individuals to undertake private mitigation measures (Baan and Klijn 2004; Terpstra et al. 2009; Plattner et al. 2006). This argument is in line with the 'motivational hypothesis', which states that people undertake precautionary measures to reduce the risk they perceive as being high (Weinstein et al. 1998). The reasoning behind the 'motivational hypothesis' can be used to demonstrate the need for awareness-raising among the population at risk, in order to reduce vulnerability by increasing the level of private mitigation. Accordingly, a growing number of empirical studies have recently investigated the factors that drive private mitigation behaviour, among which flood risk perceptions have been the most dominant (Botzen et al. 2009b; Siegrist and Gutscher 2006; Takao et al. 2004; Thieken et al. 2006; Grothmann and Reusswig 2006; Thieken et al. 2007; Miceli et al. 2008; Lindell and Hwang 2008).

However, recent empirical studies (see Table 7) that have investigated the relation between flood risk perceptions and the adoption of private flood mitigation measures do not find a statistically significant relation at all, or report only a weak relation (Kreibich et al. 2005; Siegrist and Gutscher 2006; Takao et al. 2004; Thieken et al. 2006; Thieken et al. 2007; Miceli et al. 2008; Lindell and Hwang 2008). Since risk perceptions have dominated the literature on flood mitigation behaviour, and because risk awareness-raising is an important element of current and envisaged flood management (European Union, 2007), it is imperative to understand the role that risk perceptions play in prompting private precautionary behaviour.

Table 7: Reviewed studies that examine factors of influence on private flood mitigation behaviour.

Authors	Study area	N
Botzen et al. (2009b)	Netherlands	509
Botzen and van den Bergh (2012)	Netherlands	~1000

[5] This section is based on P Bubeck, W.J.W. Botzen and J.C.J.H. Aerts (2012) A review of risk perceptions and other factors that influence flood mitigation behavior, Risk Analysis, 32(9), 1481–1495.

Grothmann and Reusswig (2006)	Germany	157
Knocke and Kolivras (2007)	USA,Virgina	300
Kreibich et al.(2005)	Germany,	1248
Kreibich et al. (2011b)	Germany	235
Lindell and Hwang (2008)	USA, Texas	321
Miceli et al. (2008)	Italy	407
Siegrist and Gutscher (2006)	Switzerland	1213
Siegrist and Gutscher (2008)	Switzerland	201
Takao et al. (2004)	Japan	2051
Terpstra (2011)	Netherlands	1071
Thieken et al. (2006)	Germany	1248
Thieken et al. (2007)	Germany	1697
Zaalberg et al. (2009)	Netherlands	516
Zaleskiewicz et al.(2002)	Poland	66

Table 8 provides an overview of the results of correlation and regression analyses, as well as the statistical significance levels found by current studies that examine the relationship between flood risk perceptions and already-adopted private mitigation measures. It shows that the majority of the reviewed studies find no or only weak relations between the two variables. Grothmann and Reusswig (2006) find small to medium values for correlations between perceived risk and four indicators that measure precautionary behaviour at statistically significant levels. A multiple regression analysis shows that perceived risk can only explain an additional 3-6 per cent of the variance in mitigation behaviour, which indicates a weak relation at best.

Table 8: Empirical findings on the relation between risk perceptions and already-adopted private flood mitigation measures

Correlations (r-values) and statistical significance (p-values)				
Independent variable	**Paper**	**Correlation**	**p-value**	
Perceived probability	Kreibich et al. (2005)	*n.a.*	*n.s*	
	Lindell and Hwang (2008)	r=0.12 and 0.18	p<0.05	
	Miceli et al. (2008)	r=.08	*n.s.*	
	Takao et al. (2004)	*n.a.*	*n.s.*	
	Thieken et al. (2006)	*n.a.*	*n.s.*	
	Thieken et al. (2007)	r= 0.2[a]	*n.s. to* p<0.05	
Perceived risk	Grothmann and Reusswig (2006)	r= 0.21- 0.30	p<0.05 to p<0.01	
Perceived risk to life	Knocke and Kolivras (2007)	n.a.	p=0.01	
Perceived risk to property	Knocke and Kolivras (2007)	n.a.	n.s.	
Perception of flood risk scale (PFRS)	Miceli et al. (2008)	r=0.11	p<0.05	
Dread of flood	Zaleskiewicz et al. (2002)	r= 0.3[b]	p<0.01	
Regression coefficients (β), Coefficient of determination (R^2), and statistical significance (p)				
Independent variable	**Paper**	**R^2**	**β**	**Significance**
Perceived probability	Lindell and Hwang (2008)[(32)]	0.01 and 0.05	*n.a.*	p<0.01
	Siegrist and Gutscher (2006)	*n.a.*	- 0.04	*n.s.*
	Miceli et al. (2008)	*n.a.*	0.08	*n.s.*

Perceived risk	Grothmann and Reusswig (2006)	0.03 to 0.06	0.02 to 0.03[c]	*n.s.to* $p<0.01$
(PFRS)	Miceli et al. (2008)	*n.a.*	0.13	$p<0.05$

[a] r values for different geographical locations are only reported if $p<0.05$ and if $r \geq 0.2$.
[b]The effect size has been calculated by the authors.
[c]Non-standardized regression coefficient.

Most of the reviewed studies measure risk perceptions by eliciting the perceived probability of a flood event (Kreibich et al. 2005; Siegrist and Gutscher 2006; Takao et al. 2004; Thieken et al. 2007; Miceli et al. 2008; Lindell and Hwang 2008). Thieken et al. (2007) find no statistically significant relation to flood mitigation behaviour in five out of six possible cases. A small to medium correlation is reported in one case. A small correlation is also reported by Lindell and Hwang (2008). However, a regression analysis shows that the perceived probability can explain only 1 per cent of the variance in protective behaviour, and 5.5 per cent of the variance in the purchase of flood insurance (Lindell and Hwang 2008). All the other studies do not find a statistically significant correlation of the perceived probability with flood mitigation behaviour. Siegrist and Gutscher (2006) employ a multiple-regression analysis, with prevention behaviour as the dependent variable, and report that perceived probability had no influence on precautionary behaviour after controlling for experience. Miceli et al. (2008) combine the perceived probability with the attitude 'fear' to derive a 'Perception of Flood Risk Scale' (PFRS), which shows a low correlation with mitigation behaviour. However, it is concluded that it is especially the emotional item 'fear' that influences mitigation behaviour rather than the perceived probability (Miceli et al. 2008).

Knocke and Kolivras (2007) examine the influence of two aspects of perceived consequences on tracking flash flood developments by individuals: namely, perceived risk to life, and perceived risk to property. While the former is found to be significantly related to a higher frequency of tracking flash floods, no significant relation was observed for the variable perceived risk to property. Zaleskiewicz et al. (2002) examine factors that influence people's decision to buy flood insurance in Poland before and after a major flood event in 1997. Risk perceptions are represented by a variable referred to as 'dread of flood', which comprises measurements of fear of flooding, perceived unavoidability of the disaster, perceived severity of losses, and perceived likelihood of flooding in the future. A comparison between respondents with, and without, flood insurance before the flood in 1997 revealed no relation between the respondents' scores on the dread factor and the decision to buy flood insurance. A statistically significant difference between the two groups was found after the 1997 flood. However, the study concludes that it is predominantly the emotional item fear that determines whether people demand flood insurance (Zaleskiewicz et al. 2002). We conclude, therefore, that the current focus on risk perceptions as a means to explain and promote private flood mitigation behaviour is not supported on both theoretical and empirical grounds.

In addition to flood risk perceptions, current research presents a large variety of factors that can potentially influence the adoption of private mitigation measures. If flood-risk perceptions are a rather weak predictor of private mitigation behaviour, then it is of interest to understand what other factors are found to be consistently related to flood mitigation behaviour. This section provides a review of the factors that influence private flood mitigation behaviour, which has not been available, so far. It aims to identify the most important factors, thereby reducing the existing complexity in the current literature. An overview of the examined factors is provided in Table 9. The table provides the p-values of the examined factors and, where applicable, effect sizes such as correlation values, standardized regression coefficients or marginal effects. It shows that factors other than risk perceptions, such as flood coping appraisals, are consistently related to flood mitigation behaviour. Coping appraisal is comprised of the three variables 'response efficacy', 'self-efficacy', and 'response cost' (Milne et al. 2000; Floyd et al. 2000). *Response-efficacy* addresses to what extent an individual believes that a protective measure effectively reduces a risk. *Self-efficacy* reflects the belief of a person as to whether he or she is personally able to actually carry out the specific measure. *Response costs* are the person's estimate of how costly it would be for him or her to actually implement the particular risk-reduction measure.

Table 9: Factors that are observed to be of influence on private flood mitigation behaviour

Independent variable	Paper	Correlations (r), standardized Beta weights (β), Odds ratios (Exp(B)), Marginal effects (ME)	Significance (p)
Experience with flooding			
Flood experience	Siegrist and Gutscher (2006)	β =0.18	p<0.001
	Lindell and Hwang (2008)	r=0.17 and 0 .14	p<0.05
	Thieken et al. (2007)	r=0.28 to 0.30[a]	n.s. to p<0.05
	Siegrist and Gutscher (2008)	Exp(B)=2.5 to 8.6[b]	p<0.01 - p<0.001
	Kreibich et al. (2005)	n.a.	p<0.05
	Takao et al. (2004)	n.a.	n.s.
	Thieken et al. (2006)	n.a.	p<0.01
	Grothmann and Reusswig (2006)[c]	r= 0.28 -0.34	p<0.01
	Kreibich et al. (2011b)	n.a.	n.s.-p<0.05
	Knocke and Kolivras (2007)	n.a.	p=0.05
(Severity of) Damage suffered	Takao et al. (2004)	n.a.	p<0.01
	Miceli et al. (2008)	r= 0.14	p<0.01
	Grothmann and Reusswig (2006)[c]	r= 0.29 - 0.39	p<0.01
Experience with Evacuation	Botzen et al. (2009b)	ME=-0.1289	n.s.
	Botzen and van den Bergh (2012)	ME=0.18	p<0.01
Fear of or worry about flooding			
Feeling of worry or fear	Miceli et al. (2008)	r=0.15 (β=0.17)	p<0.01

	Takao et al. (2004)	n.a.	n.s. to p<0.01
	Grothmann and Reusswig (2006)[c]	r=0.04 to 0.13	n.s
PFRS	Miceli et al. (2008)	r=0.11	p<0.05
Dread of flood	Zaleskiewicz et al. (2002)	r=0.3[b]	n.s.to p<0.01
Knowledge about flood hazard			
Knowledge about floods	Thieken et al. (2007)	r= 0.23 to 0.28[a]	n.s. to p<0.05
	Botzen et al. (2009b)	ME=-0.1398	p<0.05
	Thieken et al. (2006)	n.a.	p<0.01
	Kreibich et al. (2005)	n.a.	p<0.05
	Zaleskiewicz et al. (2002)	0.03[b]	n.s.
Information on floods	Miceli et al. (2008)	r=0.14	p<0.01
	Lindell and Hwang (2008)	r=0.03 and 0.12	n.s. - p<0.05
Climate change causes higher flood risk	Botzen et al. (2009b)	ME=0.1514	p<0.01
	Botzen and van den Bergh (2012)	ME=0.07	p<0.01
Socio-economic and geographic variables			
Past tenure	Lindell and Hwang (2008)	r=0.06 and 0.03	n.a.
Tenure expectations	Lindell and Hwang (2008)	r= -0.02 and 0.09	n.a.
Household size	Kreibich et al. (2005)	n.a.	p<0.05
	Zaalberg et al. (2009)	r=0.067 to -0.077	n.s.
Objective risk	Siegrist and Gutscher (2006)	β=-0.05 to 0.00	n.s.
Ethnicity	Lindell and Hwang (2008)	r= -0.11 and 0.16	n.a. and p<0.05
Perceived elevation	Zaalberg et al. (2009)	r=-0.088 to -0.355	n.s. to p<0.01
Marital status	Zaalberg et al. (2009)	r=0.093 to 0.045	n.s.
Age	Grothmann and Reusswig (2006)[c]	r=0.08 to 0.22	n.s. - p<0.01
	Botzen et al. (2009b)	ME=-0.0013	n.s.
	Miceli et al. (2008)	r=0.07 (β=0.01)	n.s. (p<0.05)
	Lindell and Hwang (2008)	r=0.02 and 0.1	n.a.
	Knocke and Kolivras (2007)	n.a.	p<0.01
	Zaalberg et al. (2009)	r=-0.012 to 0.066	n.s.
	Botzen and van den Bergh (2012)	ME=-0.03	p<0.01
Gender	Grothmann and Reusswig (2006)[c]	r=0.03 to 0.1	n.s.
	Botzen et al. (2009b)	ME=-0.0158	n.s.
	Botzen and van den Bergh (2012)	ME=-0.06	p<0.05
	Miceli et al. (2008)	r=0.12	p<0.05
	Lindell and Hwang (2008)	r= -0.02 and 0.06	n.a.
	Knocke and Kolivras (2007)	n.a.	n.s.
	Zaalberg et al. (2009)	r=-0.088 to 0.005	n.s.
Education	Grothmann and Reusswig (2006)[c]	r=-0.01 to 0.05	n.s.
	Botzen et al. (2009b)	ME=0.0490	p<0.1
	Botzen and van den Bergh (2012)	n.a.	n.s.
	Miceli et al. (2008)	r= -0.03	n.s.
	Lindell and Hwang (2008)	r= -0.01 and 0.07	n.a.
	Zaalberg et al. (2009)	r=0.001 to 0.004	n.s.
Income	Grothmann and Reusswig (2006)[c]	r= 0.11 - 0.36	n.s. - p<0.01
	Botzen et al. (2009b)	ME=0.000004	n.s.
	Lindell and Hwang (2008)	r= -0.06 and 0.08	n.a.
	Zaalberg et al. (2009)	r=0.017 to -0.075	n.s.
	Botzen and van den Bergh (2012)	ME=0.07	p<0.01
	Kreibich et al. (2005)	n.a.	p<0.05
Distance to river / water body	Miceli et al. (2008)	r=0 .14 (β=0.11)	p<0.01 (p<0.05)
	Lindell and Hwang (2008)	r= -0.16 and -0.08	n.a.
Close to river	Botzen and van den Bergh (2012)	ME=0.05	p<0.05
	Botzen et al. (2009b)	ME=0.0867	p<0.1
Rural area	Botzen et al. (2009b)	ME=0.3339	p<0.01
	Botzen and van den Bergh (2012)	ME=0.13	p<0.05
Ownership	Thieken et al. (2007)	r=0.26	n.s. to p<0.05
	Kreibich et al. (2005)	n.a.	p<0.05
	Grothmann and Reusswig (2006)[c]	r=0.11 to 0.45	n.s. - p<0.01
	Zaalberg et al. (2009)	r=0.063 to -0.028	n.s.
Hindrances for private flood mitigation			

Reliance on public flood defence	Grothmann and Reusswig (2006)[c]	r=-0.30 to 0.03	n.s. - p<0.01
Non protective responses [d]	Grothmann and Reusswig (2006)[c]	r = -0.28 - -0.41	p<0.01
	Siegrist and Gutscher (2008)	r=-0.28[b]	p<0.02
High costs	Siegrist and Gutscher (2008)	r=-0.24[b]	p<0.04
Government is perceived as responsible	Botzen et al. (2009b)	ME=-0.3094	p<0.05
Availability of government relief for damage	Botzen and van den Bergh (2012)	ME=-0.07	p<0.01
	Botzen et al. (2009b)	ME=-0.0899	p<0.05
Coping appraisals			
Effectiveness	Kreibich et al. (2005)	n.a.	p<0.05
	Zaalberg et al. (2009)	β =0.69 to 0.76[e]	p<0.0001
Self-efficacy	Zaalberg et al. (2009)	n.a.	n.s.
Coping appraisal	Grothmann and Reusswig (2006)[c]	r=-0.02 to 0.38	n.s. - p<0.01

[a] r values for different geographical locations are only reported if $p<0.05$ and if $r \geq 0.2$.
[b] The effect size has been calculated by the authors.
[c] Four different precautionary measures are assessed separately from each other, which results in four different correlation coefficients. Only statistically significant correlations ($p<0.05$) are included in the table.
[d] Non-protective responses refer to factors such as wishful thinking, fatalism, or hopelessness.
[e] Non-standardized regression coefficient.

7. Detailed insights into the influence of flood-coping appraisals on mitigation behaviour[6]

A factor that has been shown to be consistently related to flood mitigation behaviour is what is referred to as flood-coping appraisal (Grothmann and Reusswig 2006; Zaalberg et al. 2009). The concept of coping appraisal originates from Protection Motivation Theory (PMT), which is a widely adopted psychological model that explains decision making in response to threats (Rogers 1975, 1983). Within PMT, coping appraisal refers to the cognitive process that people undergo when they evaluate possible actions in response to the perceived threat and their own ability to avert or avoid a certain risk. It consists of three individual components referred to as 'response efficacy', 'self-efficacy', and 'response cost'. Studies that have examined flood-coping appraisal consistently found statistically significant relationships with flood mitigation behaviour (Grothmann and Reusswig 2006; Zaalberg et al. 2009). This suggests that flood-coping appraisal is an important variable to understand flood-mitigation behaviour and, therefore, is important for flood-risk communications.

Even though it has been shown that flood-coping appraisal is an important explanatory variable, the literature on this subject is still scarce, in general, and little is known about the independent influence of response efficacy, self-efficacy, and response cost on household decisions to implement different flood-mitigation measures, in particular. A limitation of the recent literature is that it applied a single variable 'coping appraisal' in statistical models that explain flood mitigation behaviour, instead of examining each component separately (e.g. Grothmann and Reusswig 2006). With regard to flood-risk communications, it is important to gain further insights into the influence of the individual components of coping appraisal on protective behaviour. Such insights could provide important information for flood-risk management policies, because it indicates whether risk communications should emphasize the effectiveness of flood mitigation measures (response-efficacy), should focus on providing practical guidelines on how to deploy such measures (self-efficacy), or, whether the costs of protective measures should be addressed when stimulating flood mitigation behaviour (response cost).

To gain insights into the influence of the three individual components of flood-coping appraisal on precautionary behaviour, this study presents data from a survey conducted among

[6] This section is based on P. Bubeck, W.J.W. Botzen, H. Kreibich and J.C.J.H. Aerts (2012) Detailed insights into the influence of flood-coping appraisals on mitigation behaviour, Global Environmental Change – Human and Policy Dimensions, under review.

752 flood-prone households along the German part of the river Rhine. It examines, how response efficacy, self-efficacy, response cost and a wide range of other factors relate to the implementation of four different types of flood-mitigation measures: namely, structural building measures, adapted building use, flood barriers, and the purchase of flood insurance.

In line with our hypothesis, we find that flood coping variables make a significant contribution to all models explaining four different types of flood mitigation behaviour (Table 10). Moreover, flood experience, the social environment and non-protective responses importantly influence flood mitigation behaviour. The social environment variable captures whether friends and neighbours implemented a flood mitigation measures. Non-protective responses refer to variables such as wishful thinking (a flood will not happen to me) or postponement (measures are important but I will implement these later).

Table 10: Overview of significant variables and p-values of the four best-fitting models of the four different types of mitigation measures

	Response efficacy	Self-efficacy	Perceived probability	Perceived consequence	Avoidance	Wishful thinking	Postponement	Protected Area	Urban area	Age	Income	Experience	Social Environment
Structural measures		.002				.000	.002	.029			.015	.049	.008
Adapted use	.002		.003				.000					.006	.000
Flood barriers	.001	.004		.007			.000			.010			.000
Flood insurance	.000	.000			.005			.001	.002			.004	.006

8. Recommendations

The findings of this report have several important implications for integrated flood risk management policies, which are increasingly implemented in Germany, Europe and on a global level. According to the projected effects of climate change, floods will become more frequent and more extreme in many regions, and, could increasingly affect areas with little prior flood experience. Given the finding that flood experience strongly influences the precautionary behaviour of flood-prone residents, this also implies that highly vulnerable areas will be increasingly affected. Moreover, even among households that currently live in highly flood-prone areas, a large share of households did not undertake any precautionary measure.

Therefore, in order to successfully manage the transition to integrated flood risk management approaches, further efforts are needed to reach a higher level of precautionary measures among households at risk of flooding. A first important step in this direction would be to overcome the existing lack of knowledge and lack of support of flood-prone households regarding their increased responsibility to contribute to flood damage reduction in contemporary flood risk management.

Another approach to increase the level of flood mitigation measures are effective and tailored risk communications. Currently, especially risk awareness raising is an important tool to stimulate flood mitigation behaviour in contemporary and envisaged flood risk management. Although it is obvious that people need to be aware of a certain risk to possibly react to it, the findings of the report indicate that the predominant focus on risk awareness (or perception) will not be sufficient to manage the intended transition to more integrated flood management approaches. It is suggested that a sole focus on risk awareness raising can potentially even lead to non-protective responses, such as fatalism, denial, and wishful thinking. Given the important role that coping appraisals, and in particular self-efficacy and response-efficacy play in translating high risk perceptions into protective behavior, these aspects should receive greater attention in risk communication policies and future research on flood mitigation behavior. Risk communications should emphasize that flood mitigation measures at the household level can effectively prevent or reduce flood damage. Moreover, practical advice should be provided to households on how to deploy such measures.

That effective communication which emphasizes the importance of precautionary behaviour can indeed result in a measurable increase in the level of implemented mitigation measures is also supported by the findings regarding the long-term development of flood mitigation measures. These indicate that workshops that were offered to flood-prone households by civil society and international river basin organisations can be a successful mechanism to increase the level of precaution. Hence, governmental authorities should offer and use such communication platforms to provide guidance to flood-prone households in order to further stimulate flood mitigation behaviour. Existing civil society organisations, such as the "Hochwassernotgemeinschaft Rhein e.V." or the "Bürgerinitiative Hochwasser Köln-Rodenkirchen" seem promising organisations to convey this message to the flood-prone population.

However, given the strong influence of flood experience on the precautionary behaviour of flood prone households, additional policies that go beyond purely voluntary precautionary behaviour seem unavoidable to reach an adequate level of preparedness also in areas with little prior flood experiences. The finding that flood mitigation measures are often appraised positively, but are postponed as long as they are not considered as absolutely necessary by the respondents shows that there is room for alternative policies to overcome this passiveness in order to increase the preparedness of people of risk. These policies should not only apply to current flood zones (e.g. the 1/ 100 year flood zone) but should anticipate the effects of climate change on these flood zones. For instance, long-term flood insurance policies could provide financial incentives for households that implement appropriate measures, by granting premium reductions, or, by providing practical advice in terms of their implementation (self-efficacy). The findings of this report show that this potential is currently unexploited by German insurers. Another approach to overcome the low-level of preparedness of flood-prone households would be to integrate more stringent requirements in existing building codes, and to enforce these more strictly.

That it can be a rewarding undertaking to increase the level of flood mitigation measures at the household level is demonstrated by our finding that flood prone households considerably contributed to damage reduction could thus contribute to integrated flood risk management.

9. Conclusions

This research shows that the risk from extreme flood events along the Rhine will not be stationary and might increase considerably during the coming decades. The implementation or strengthening of flood defense measures, such as retention basins and dike heightening, might prevent the increase in flood probability and thus the contribution of climate change to future flood risk. Information on the long-term development of private flood mitigation measures by households is also important. Data from a survey along households along the Rhine in Germany shows direct disaster experience is an important trigger for the implementation of flood mitigation measures. A significantly increased rate of implementation can be consistently observed in the aftermath of flood events between 1980 and 2011. In addition, it is indicated that also workshops offered to flood-prone households by civil society and international river basin organisations, which emphasize the need for precautionary behaviour, can be a successful mechanism to increase the level of preparedness of flood-prone households. As far as the current implementation level of flood mitigation measures is concerned, it is found that a considerable share of respondents did not implement a single flood mitigation measure, despite a high vulnerability of the surveyed households to floods.

The damage-reducing effect of flood mitigation measures was examined by comparing the precautionary behaviour and damage suffered of households that were affected by two severe floods in 1993 and 1995. This comparison demonstrated that the substantial damage reduction observed in 1995 can indeed be attributed to an improved preparedness of the flood-prone population during the latter event. Moreover, it is found find that even respondents who did not undertake any precautionary measure themselves in 1993 and 1995, still benefitted from the improved preparedness of others due to lower levels of contaminated flood waters. In order to effectively stimulate flood precautionary behaviour, better knowledge about the factors that influence individual's decisions to protect themselves against flood impacts is therefore essential for risk communications. Such effective risk communication is needed to increase the preparedness of the population facing flood risk in order to successfully manage the transition from traditional flood control approaches to integrated flood-risk management in Europe and worldwide. The survey shows that flood-coping appraisals are also important variables of influence on four different types of flood mitigation behavior

10. Project publications and PhDs

The scientific output (peer-reviewed articles) of the project *Assessment of upstream flood risk in the Rhine Basin (HSGR02)* contributed to the completion of two PhD theses at the Institute for Environmental Studies (IVM) at the VU University Amsterdam. These two theses are:

Te Linde, Aline (2011). Rhine at Risk? Impact of climate change on low-probability floods in the Rhine basin and the effectiveness of flood management measures. PhD Thesis, VU University Amsterdam, The Netherlands.

Bubeck, Philip (2012). Private flood mitigation measures in a changing risk environment. PhD Thesis, VU University Amsterdam, The Netherlands, (to be defended).

Publications:

Te Linde, A. H., Bubeck, P., Dekkers, J. E. C., De Moel, H. & Aerts, J. C. J. H. 2011. Future flood risk estimates along the river Rhine. Natural Hazards and Earth System Sciences, 11(2), 459-473.

In Europe, water management is moving from flood defence to a risk management approach, which takes both the probability and the potential consequences of flooding into account. It is expected that climate change and socio-economic development will lead to an increase in flood risk in the Rhine basin. To optimize spatial planning and flood management measures, studies are needed that quantify future flood risks and estimate their uncertainties. In this paper, we estimated the current and future fluvial flood risk in 2030 for the entire Rhine basin in a scenario study. The change in value at risk is based on two land-use projections derived from a land-use model representing two different socio-economic scenarios. Potential damage was calculated by a damage model, and changes in flood probabilities were derived from two climate scenarios and hydrological modeling. We aggregated the results into seven sections along the Rhine. It was found that the annual expected damage in the Rhine basin may increase by between 54% and 230%, of which the major part (~ three-quarters) can be accounted for by climate change. The highest current potential damage can be found in the Netherlands (110 billion €), compared with the second (80 billion €) and third (62 billion €) highest values in two areas in Germany. Results further show that the area with the highest fluvial flood risk is located in the Lower Rhine in Nordrhein-Westfalen in Germany, and not in the Netherlands, as is often perceived. This is mainly due to the higher flood protection standards in the Netherlands as compared to Germany.

Bubeck, P., De Moel, H., Bouwer, L. M. & Aerts, J.C.J.H. 2011. How reliable are projections of future flood damage? Natural Hazards and Earth System Sciences, 11(12), 3293-3306.

Flood damage modelling is an important component in flood risk management, and several studies have investigated the possible range of flood damage in the coming decades. Generally, flood damage assessments are still characterized by considerable uncertainties in stage-damage functions and methodological differences in estimating exposed asset values. The high variance that is commonly associated with absolute flood damage assessments is the reason for the present study that investigates the reliability of estimates of relative changes in the development of potential flood damage. While studies that estimate (relative) changes in flood damage over time usually address uncertainties resulting from different projections (e.g. land-use characteristics), the influence of different flood damage modelling approaches on estimates of relative changes in the development of flood damage is largely unknown. In this paper, we evaluate the reliability of estimates of relative changes in flood damage along the river Rhine between 1990 and 2030 in terms of different flood-damage modelling approaches. The results show that relative estimates of flood damage developments differ by a factor of 1.4. These variations, which result from the application of different modelling approaches, are considerably smaller than differences between the approaches in terms of absolute damage estimates (by a factor of 3.5 to 3.8), or than differences resulting from land-use projections (by a factor of 3). The differences that exist when estimating relative changes principally depend on the differences in damage functions. In order to improve the reliability of relative estimates of changes in the development of potential flood damage, future research should focus on reducing the uncertainties related to damage functions.

Bubeck, P., Botzen, W.J.W. & Aerts, J.C.J.H. 2012. A review of risk perceptions and other factors that influence flood mitigation behavior. Risk Analysis, online first, **DOI: 10.1111/j.1539-6924.2011.01783.x.**

In flood risk management, a shift can be observed toward more integrated approaches that increasingly address the role of private households in implementing flood damage mitigation measures. This has resulted in a growing number of studies into the supposed positive relationship between individual flood risk perceptions and mitigation behavior. Our literature review shows, however, that, actually, this relationship is hardly observed in empirical studies. Two arguments are provided as an explanation. First, on the basis of protection motivation theory, a theoretical framework is discussed suggesting that individuals' high-risk perceptions need to be accompanied by coping appraisal to result in a protective response. Second, it is pointed out that possible feedback from already-adopted mitigation measures on risk perceptions has hardly been considered by current studies. In addition, we also provide a review of factors that drive precautionary behavior other than risk perceptions. It is found that factors such as coping appraisal are consistently related to mitigation behavior. We conclude, therefore, that the current focus on risk perceptions as a means to explain and promote private flood mitigation behavior is not supported on either theoretical or empirical grounds.

Bubeck, P., Botzen, W.J.W., Kreibich, H. & Aerts, J.C.J.H. (2013). Detailed insights into the influence of flood-coping appraisals on mitigation behaviour. *Global Environmental Change*, **DOI:10.1016/j.gloenvcha.2013.05.009.**

Insights into flood mitigation behaviour are important because of the ongoing shift to risk-based flood management approaches in Europe and worldwide, which envisage a contribution from flood-prone households to risk reduction. The recent literature on factors that influence flood mitigation behaviour indicates that flood-coping appraisal is an important variable to understand and explain flood mitigation behaviour. Coping appraisal originates from Protection Motivation Theory (PMT), and refers to the cognitive process that people undergo when evaluating their own ability to avoid a certain risk. However, the empirical literature on the importance of coping appraisal is still scarce, and, in particular, little is known about the independent influence of the three single components of coping appraisal on precautionary behaviour: namely, response efficacy, self-efficacy, and response cost. This study presents the results of a recent survey among 752 flood-prone households along the river Rhine in order to provide detailed insights into the influence of the components of flood-coping appraisal on four different types of flood mitigation behaviour: structural building measures, adapted building use, the deployment of flood barriers, and the purchase of flood insurance. The results confirm that flood-coping appraisal is an important variable in terms of precautionary behaviour. In particular, both response efficacy and selfefficacy contribute to the models which explain the four different types of flood-mitigation behaviour. Based on these findings, it is concluded that risk communication should focus more strongly on the potential of flood-mitigation measures to effectively reduce or avoid flood damage, as well as on information about how to implement such measures in practice.

Bubeck, P., Botzen, W.J.W., Kreibich, H. & Aerts, J.C.J.H. 2012. Long-term development and effectiveness of private flood mitigation measures: an analysis for the German part of the river Rhine. Nat. Hazards Earth Syst. Sci., 12, 3507-3518, 2012. www.nat-hazards-earth-syst-sci.net/12/3507/2012/. **doi:10.5194/nhess-12-3507-2012**

Flood mitigation measures implemented by private households have become an important component of contemporary integrated flood risk management in Germany and many other countries. Despite the growing responsibility of private households to contribute to flood damage reduction by means of private flood mitigation measures, knowledge on the long-term development of such measures, which indicates changes in vulnerability over time, and their effectiveness, is still scarce. To gain further insights into the long-term development, current implementation level and effectiveness of private flood mitigation measures, empirical data from 752 flood-prone households along the German part of the Rhine are presented. It is found that four types of flood mitigation measures developed gradually over time among flood-prone households, with severe floods being important triggers for an accelerated implementation. At present, still a large share of respondents has not implemented a single flood mitigation measure, despite the high exposure of the surveyed households to floods. The records of household's flood damage to contents and structure during two consecutive flood events with similar hazard characteristics in 1993 and 1995 show that an improved preparedness of the population led to substantially reduced damage during the latter event. Regarding the efficiency of contemporary integrated flood risk management, it is concluded that additional policies are required in order to further increase the level of preparedness of the flood-prone population. This especially concerns households in areas that are less frequently affected by flood events.

11. Societal impact and outreach of the project

The findings of the KvK project *Assessment of upstream flood risk in the Rhine Basin (HSGR02)* were presented at various instances to the scientific community and policy makers. Amongst other things, this included the Global Risk Forum in Davos, the General Assembly of the European Geoscience Union (EGU) in Vienna and the German Committee for Disaster Risk Reduction. Moreover, the project findings were discussed in-depth with relevant policy makers of the riparian countries of the Rhine.

In addition to a close cooperation with Rijkswaterstaat in the course of the project in the Netherlands, Philip Bubeck presented and discussed the project's findings twice during meetings of the expert group on flood risk of the International Commission for the Protection of the Rhine (ICPR) in Koblenz. This was important, since the ICPR also is interested in following up the EU Flood Directive, and this project provides uniform methods that enable implementing the recommendations of the flood directive. Co-funding to the project was provided by Rijkswaterstaat.

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