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Damage-reducing measures to manage flood risks in a changing climate

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Abstract

Damage due to floods has increased during the last few decades, and further increases are expected in several regions due to climate change and a possibly growing vulnerability. To address the projected increase in flood risk, a combination of structural and non-structural flood risk mitigation measures is considered as a promising adaptation strategy. Such a combination takes into account that flood defence systems may fail, and prepares for unexpected crisis situations via land-use planning and private flood damage reduction e.g. via building precautionary measures. Private measures like shielding with water shutters or sand bags, building fortification or safeguarding of hazardous substances are often voluntary; they demand self-dependent action by people or companies at risk. It is believed that these measures are especially effective in areas with frequent flood events and low flood water levels, but some types of measures showed a significant damage-

reducing effect also during extreme flood events. This overview presents information about different damage-reducing measures, their state of implementation and the damage reducing effects of such measures, particularly reporting results of the project “Climate proof flood risk management” of the Dutch Knowledge for Climate (KFC) program.

1. Introduction

Flood damage in Europe and worldwide has increased considerably in recent decades, particularly due to an on-going accumulation of people and economic assets in risk prone areas (Barredo, 2009; Merz et al. 2012). For instance, the large-scale flood event in June 2013 in the Elbe and Danube catchments caused losses in the range of 8 to 12 billion € in Germany. A special reconstruction aid fund of 8 billion € has been implemented by the federal states and the German federal government (Aufbauhilfegesetz came into effect 19th July 2013). The 2013 flood is comparable in respect of region affected, intensity and damage to the extreme summer flood in 2002 (Becker & Grünewald 2003) which caused damage of €11.6 billion in Germany (Thieken et al., 2007). It is expected that flood risk will continue to rise in many regions due to a combination of climate change and an increase in vulnerability (Kundzewicz et al., 2005; 2013), e.g. due to increasing flood plain occupancy, value increase in endangered areas and changes in the terrestrial system, e.g. land cover changes and river regulation. For instance, winter discharges and consequently flood probabilities along the Rhine are expected to increase in coming decades (Te Linde et al., 2011).

Against the background of the projected increases in flood risk due to the effects of climate change, growing exposure and possibly increased vulnerability, as well as the considerable uncertainties associated with these developments, flood risk management has increasingly shifted towards more integrated flood risk management concepts in many European countries and world-wide in recent decades (Bubeck et al., 2012b). In addition to flood prevention by means of flood defence measures such as dikes, the latter also aim at preventing or reducing damage in case of a flood event through non-structural measures like land-use planning, measures taken at the building level and disaster response. For instance, in the Netherlands a new policy framework has been adopted named “Multi-Layer Safety (MLS)”, which takes a risk-based flood management approach (Ministry of Transport and Water et al., 2009). This framework addresses three layers: i) prevention, ii) damage reduction through sustainable spatial planning and iii) crisis control and evacuation.

Maybe the most straightforward solution to reduce flood risk is to avoid (the most) dangerous places in the first place so little to no harm can come to human life and property. Historically, this was in essence the very first flood management measure employed by civilization. Looking at early human settlements, they are in many cases founded on elevated grounds like outcrops of bedrock, moraines or river dunes (Stalenberg and Vrijling, 2006). However, with increasing population pressure and due to the benefits associated with settling close to river courses (Kummu et al., 2011), towns expanded considerably, forcing the occupation of ever more dangerous lands; a process that continues up to this day (De Moel et al. 2011). This expansion into flood-prone areas has given rise to the development of extensive flood defense systems. While generally reducing the flood risk, the construction of levees can, paradoxally, also increase flood risks in that it promotes new developments, which increase the potential damage a flood would cause, known as the 'levee effect' (see e.g. Pielke, 1999; Di Baldassarre et al., 2009; Lane et al., 2011). Therefore, spatial planning is an important tool to manage flood risks, and is part of the portfolio in various countries, supplementing flood defense structures (Burby et al., 1999; APFM, 2007; Neuvel and Van den Brink, 2009; Glavovic 2010).

Where villages or towns already exist, flood damage must be kept as small as possible. Previous studies have indicated that flood mitigation measures adopted by private households or companies, such as flood-adapted building use, the deployment of mobile flood barriers or securing of contamination sources, can effectively reduce damage (e.g. Kreibich et al., 2005; 2007; 2011b). Accordingly, private contribution to damage and thus risk reduction has become an important component of contemporary flood risk management portfolios in many countries (Bubeck et al., 2012b). In Germany, for instance, the responsibility of flood-prone residents and business to contribute to damage prevention gained prominence following major flood disasters along the river Rhine in 1993 and 1995 (Environment Agency, 2010). The disastrous floods along the River Elbe and the River Danube in 2002, again revealed significant regulation and implementation deficits in terms of damage prevention (Environment Agency, 2010, Petrow et al., 2006). As a result, the national framework law was revised to provide more stringent and uniform regulations in terms of spatial planning and damage prevention by households and businesses (Wasserhaushaltsgesetz, 2009). Even the Netherlands, which long-time focused solely on structural flood defences recently started to consider flood mitigation measures as a complementary option for areas that are not protected by the dike ring system (Bubeck et al., 2012b; Van Vliet and Aerts, 2014).

Even though the contribution of land use planning and private damage reduction have become an important component of many contemporary flood risk management portfolios, knowledge remains scarce and is often confined to specific regions or case studies. For instance, the benefits and costs of measures at the household level are not well known yet, just as the underlying motivations to implement such measures. In addition, finding the balance between minimising flood risk and other interests in land use planning (e.g. desire for river view houses) remains a challenge as the often low effectiveness of policies shows (Pottier 2000, 2002, Holway and Burby, 1993). The objective of this overview is the presentation of information about different damage-reducing measures, their state of implementation and the damage reducing effects of such measures, particularly reporting results of the project “Climate proof flood risk management” of the Dutch Knowledge for Climate (KFC) program.

2. Land use planning

2.1 Flood hazard mapping and zoning

Taking action to avoid dangerous areas starts with the identification of such areas. This is commonly referred to hazard mapping. Hazard mapping is common in many places. For instance, De Moel et al. (2009) illustrate that as good as all European countries have hazard maps available, or are in the process of producing them to comply with the EU flood directive. General methodologies for flood hazard mapping are detailed by Merz et al. (2007) and De Moel et al. (2009) and are described for several levels of detail elsewhere in this special issue (De Moel et al., this issue). Most commonly, flood hazard mapping involves the determination of flood extents for synthetic events with a specific return period (i.e. the 100-year flood zone). For instance, the Norwegian flood inundation map project was initiated in 1995 by the Norwegian Water Resources and Energy Directorate (NVE). The aim is to reduce flood damage through improved land use planning and emergency preparedness (Berg, 2002). Maps are created for six different flood levels (Hoydal et al., 2000). The guidelines recommend implications for land use planning and flood protection, e.g. it was defined that residential buildings need to be safe against a 100-year flood, and industry and infrastructure need to be safe against a 200-year flood (Hoydal et al., 2000). There are, however, more indicators for the severity of a flood besides flood extent, such as flood depth, flow velocity, and rate of rising of the water (de Moel et al. 2009), which can also be mapped. In practice, flood extent and depth are the most common ones used (Figure 1). Flood extent because it allows depicting events with various intensities in a single map, and flooding depth because it is generally seen as the most important parameter influencing flood damage (see e.g. Smith, 1994; Kreibich et al., 2009; Merz et al., 2010).

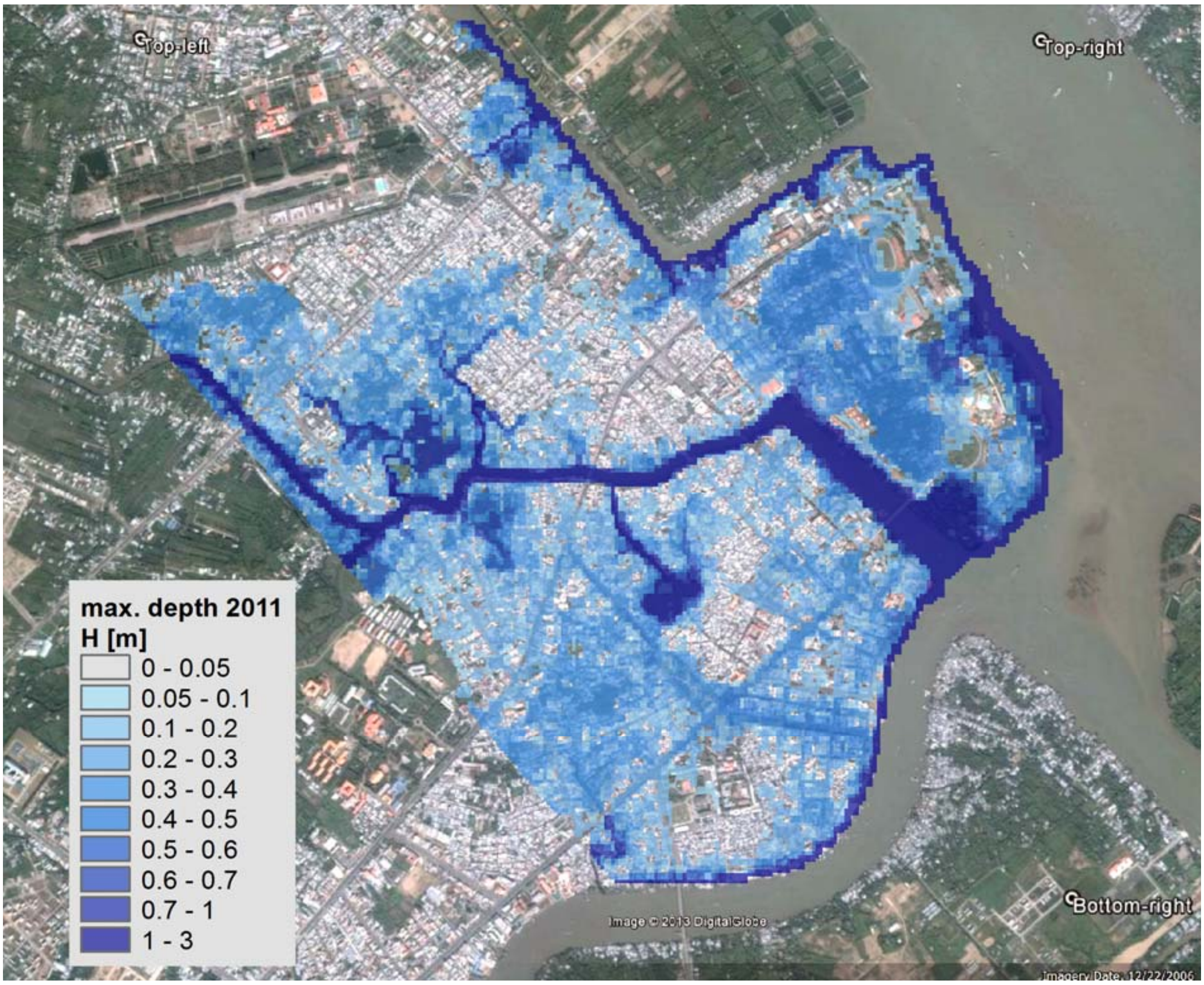

Figure 1: Example of a flood extent and water depth map: Simulated maximum water depth of the 2011 Mekong flood in Can Tho, Vietnam (Apel et al. in prep.; http://www.wisdom.eoc.dlr.de/en/content/combined-fluvial-and-pluvial-flood-hazard-analysis-can-tho-city)

In some cases, several indicators for the severity of a flood are combined into distinct danger classes using, for instance, a matrix. These different classes can then be used for zoning, as done in Switzerland (Zimmerman et al., 2005). For the Netherlands, De Bruijn and Klijn (2009) created a hazard rating map to define risky places, which was a combination of the design level of the defence, the rate at which the water table rises and the resulting water depth. All three factors were scaled between 0-1 and averaged to get the combined hazard rating (De Bruijn and Klijn, 2009). Another hazard indicator that is potentially useful for zoning policy is local individual risk (Pieterse et al., 2013). It is defined as the annual probability that a virtual person dies as a result of a flood in a specific location. Local individual risk aggregates flood events with different probabilities, using water depth, the rate the water table rises and the effect of evacuation to estimate the probability of floods causing a fatality (Beckers and De Bruijn, 2011).

Hazards maps form the basis for integrating flood considerations into spatial planning policy to reduce flood risk. The visualization and communication of such maps is important in determining whether they are used successfully and adequately (Fuchs et al., 2009; Meyer et al., 2012). For instance, maps should contain a limited amount of components and classes, with a legend that is sufficiently large. Maps should be tailored for different audiences like strategic planners, emergency managers or general public (Meyer et al., 2012). Participative workshops using interactive (mapping) tools can help in getting the information across (Eikelboom and Janssen, 2013; Arciniegas et al., 2013).

Zoning policies rely heavily on the detail and quality of hazard maps defining different zones. This can lead to various complications. For instance, the production of detailed hazard maps can cause delays in the implementation process of a policy. Also, the creation of hazard maps can become a politicized effort, where local communities have an interest in underestimating the hazard (Fleischhauer, 2005). The issue of updating maps is important in this regard as well. This has been recognized as a problem in the USA by Burby (2001), and became painfully obvious when Sandy hit the northeast coast in 2012. Updated maps where released shortly after Sandy, which showed a substantial increase in flood-prone area compared to the old maps developed over 25 years earlier[1]. Similar problems were experienced along the Lower Fraser river in Canada, where model results showed that flood levels would be much higher than expected from the old flood maps dating from 1968 (Fraser Basin Council, 2006). Shrubsole et al. (1997) and Benoît et al. (2003) showed that the development as well as the publication of flood hazard maps had no effect on the decision about building in flood-prone areas and the development of the damage potential in several Canadian regions.

2.2 Flood risk reduction via land use planning

The contribution of spatial planning towards the reduction of flood risk can take many forms. The most obvious way is to implement **zoning regulations**. This entails the determination of areas with a certain flood risk (i.e. the 100 year flood zone) and setting up certain land-use requirements for these zones. Such requirements could constitute, for instance: a complete ban, restricting certain uses, requiring certain building standards, giving recommendations, providing information to inhabitants in certain zones (Merz et al., 2007). Zoning is used in various countries to manage flood risks. In Canada between 1975 and 1999 under the Flood Damage Reduction Program (FDRP) floodplains in 900 communities were mapped, and 320 flood risk areas designated (Fraser Basin Council and Arlington Group, 2008). In Germany, the area affected by a 100-year flood plays an important role for flood risk

[1] http://www.region2coastal.com/faqs/advisory-bfe-faq

management (Marco, 1994, Watt, 2000). In this area, land use is often restricted and flood defences (e.g. levees, flood retention basins) are frequently designed to protect existing settlements up to this flood level (Petrow et al. 2006). In France and Switzerland, for instance, there are zoning policies including zones where developments are completely prohibited, and zones where there are conditional uses or construction requirements (Fleischhauer, 2005; Zimmerman et al., 2005). Switzerland defines four zones depending on the probability and intensity (inundation depth, flow velocity), that range from "severe hazard" (prohibited zone for construction and development) to "residual risk" (information, special requirements for building) (Egli, 2000; BWG, 2001). In Spain, spatial planning of flood areas is included in the Water Act and some of its regulations (Menendez, 2000). There are four zones, for which restrictions in land use are given: the "channel" (10-year flood zone), a restricted-use area, i.e. a five meter buffer on either side of the channel, a surveillance zone, i.e. a 100 m wide strip on either side of the channel and a flood risk zone, i.e. theoretical levels during floods with a return period of 500 years. In the first three zones authorization is required for any kind of construction.

Zones that completely ban developments are not always incorporated in zoning policies. In the USA and Canada, zoning is linked to building requirements in that they require a certain elevation of the floor level of houses in flood zones. In Canada these requirements come from the provincial or local level, e.g. provincial guidelines in British Columbia state that the floor of houses should be located above the 1 in 200 years flood level (Ministry of Water Land and Air Protection, 2004). In the USA zoning is linked with the National Flood Insurance Program (NFIP), in which many (more than 18000) communities participate who otherwise are not eligible for federal disaster aid and grants or loans for construction in floodplains (Holway and Burby, 1993). These building standards in the USA apply to all new buildings, and buildings that are substantially renovated (>50% of the value of the building) and are directly linked to flood insurance (Aerts and Botzen, 2011). In Germany and the Netherlands, municipalities play an important role for flood precaution as they can specify measures for the minimization of the damage potential for flood-prone areas (Böhm et al., 2004). Their land use plans tell which land use is allowed on each plot and development plans need to demonstrate 'good spatial planning' (Van Vliet and Aerts, 2014), and in this sense flood issues could, theoretically, be incorporated. De Moel et al. (2009) showed that in various European countries, there is not so much a zoning policy, but there is an obligation to take flood hazard zones into account somewhere during the spatial planning process (e.g. in the UK, Finland). In the Netherlands, flood zoning is currently used only in flood plains of rivers outside the embankments, with the goal to limit building in order to maintain the rivers' discharge and storage capacity.

Where zoning policies can be used to limit the exposure to flooding of people and assets, spatial planning can theoretically also play a role in **limiting fatalities** by optimizing the possibility to reach safe places in case of flooding, be it within the flooded region (vertical evacuation, for instance to higher floors or designated flood shelters) or out of the affected region (horizontal evacuation). This is apparent in Hamburg (HafenCity), where walkways have been created above extreme flood levels. In addition, spatial planning can facilitate the evacuation of people away from threatened areas by making sure the main road network is elevated and thus able to be used longer in case of flooding. Old levees or local embankments can potentially be used for this and may have an extra compartmentalization effect (Klijn et al., 2010; Koks et al., 2014). Such compartmentalization could limit the flood extent and thus fatalities and damage as well.

Whilst spatial planning can play a role in limiting the consequences of flood events, it can also play a role in **limiting the flood hazard**. In the last couple of decades, the philosophy of giving space back to rivers in order to reduce peak water levels has gained quite some traction. In such an approach, spatial planning is used to give back more space to the river, often coupling uses with nature or agriculture. Measures include, for instance, relocating dykes, lowering floodplains, deepening channels, using retention areas or creating bypasses (Hooijer et al., 2004). In the Netherlands this is known as 'Room for the River', a 2.3 billion euro program (Ruimte voor de Rivier, 2012) encompassing many projects throughout the country and the flood zoning regulations for un-embanked areas. It forbids most new developments in the un-embanked areas. Its secondary goal is to increase the spatial quality of the river landscape via nature development and recreation. The policy has been incorporated in the spatial planning legislation (Ministry of Transport Public Works and Water Management, 2006; Ministry of Infrastructure and the Environment, 2011). In the UK this is known as 'making space for water' (DEFRA, 2005), and also in the USA this philosophy is used in various places (see Cho, 2011).

While theoretically spatial planning policies have a large potential to reduce flood risk, research on the effectiveness of spatial policies on reducing flood risk shows that it can be effective in reducing a risk increase, but has failed to stop the encroachment of floodplains. Moreover, such policies mainly target new developments, whilst there is usually already a considerable building stock present.

Pottier et al. (2005) investigated the effect of policies in France, where there is a national system with mandatory risk zones and insurance; and in England and Wales, where there is a system based on national guidance and local attention to flooding. They illustrate that in both countries the pressures on floodplains continues to grow, despite the existing regulations. In France, case studies show that floodplain encroachment continued to take place, though the policies probably lowered the pace and developments mainly took place in the moderate risk areas (Pottier 2000, 2002). In

England the flood-risk advice given by the Environment Agency was often taken into consideration, but many developments still took place in flood-prone areas. Similarly in the USA, Holway and Burby (1993) show that the NFIP program has succeeded in reducing flood losses through the elevation of buildings, but had little effect on the rate of floodplain development. Lastly, if there is not a clear penalty to non-compliance, there is a potential that rules are simply not followed as has been illustrated e.g. in Poland (Wanczura, 2005).

While reducing flood risk and limiting floodplain encroachment make sense from a risk management point of view, the larger context should always be kept in mind. The benefits of developing flood-prone areas to society may outweigh the increase in average annual damage or other costs (Green et al., 2000). Additionally, implementation of zoning regulations may also have negative effects. For instance, raising new build plots in existing build up areas, for instance, cause height differences that make the area less accessible for disabled and elderly (Van Vliet and Aerts, 2014). Moreover, stringent policies on building codes and rigid enforcement may hamper urban rehabilitation, as has been shown in New Jersey (Burby et al., 2006).

3. Private flood damage reduction

3.1 Implementation of private damage reducing measures

Where settlements already exist in flood prone areas, private precautionary measures can reduce flood damage. Private households and companies can undertake various damage reducing measures: These include precautionary measures taken in and around exposed buildings as well as preparatory measures such as collecting information about flood risk and flood protection or participation in neighbourhood help in order to enable a more effective reaction in case of an event. Particularly, building precautionary measures mitigate damages in flood-prone areas (ICPR, 2002; ABI, 2003; Kreibich et al., 2005). Building precautionary measures aim at minimising damages by means of flood adapted use and equipment of buildings, i.e. wet flood proofing or by means of sealing, reinforcement and shielding, i.e. dry flood proofing (ICPR 2002). Examples of wet flood proofing are the following: to adapt the building use which means that cellars and endangered storeys are not used cost-intensively; to adapt the interior fitting which means that in endangered storeys, only waterproofed building material and movable small interior decoration and furniture should be used; or to safeguard possible sources of contamination, such as an oil tank of a heating system. Dry flood proofing measures include, for instance, to adapt the building structure, e.g. via an elevated configuration; to waterproof seal the cellar, e.g. by constructing the basis and walls of buildings out of concrete that is non-permeable; or to deploy mobile flood barriers such as temporary flood guards. In Germany, the federal states have laws stipulating that oil heating systems, including oil tanks, have to be flood-proofed within flood risk areas (e.g., VAwS-Baden-Württemberg, 2005; VAwSHessen, 2006; VAwS-Bayern, 2008). When new houses or even settlements are being built or extensively renovated, an elevated configuration or the construction of buildings without cellars should be considered. Other precautionary measures available to individuals are described in Holub and Hübl (2008).

Information material promoting private precautionary measures have been published, amongst others, by several German ministries and cities (BMVBW, 2002; MURL, 2000; MUF, 1998; Stadt Köln, 1994), the UK Environment Agency (Environment Agency, 2003a, b; Hampshire Flood Steering Group, 2002; SEPA, 2003), the US Federal Emergency Management Agency (FEMA) and Army Corps of Engineers (USACE) (FEMA, 1998a,b, 1999; USACE, 1995, 1996), and in Australia (DECC-NSW, 2008). Taking precautionary measures often demands self-reliant behaviour on behalf of the private households or companies since most measures are voluntary (Heiland, 2002). Raschky (2008) highlights the effects of the institutional framework on human behaviour and the incentives it sets. There are few laws (e.g., building codes) requiring homeowners to take precautionary measures. However, during recent years in Germany private households' responsibility for flood damage reduction has been increasingly emphasized and embedded into flood risk management (Environment Agency, 2010). According to § 5 of the German Federal Water Resource Act that was enacted in 2009, every person that could be affected by a flood is obliged to undertake appropriate actions that are reasonable and within one's means to reduce flood impacts and damage (Wasserhaushaltsgesetz, 2009).

Previous studies have shown that personal flood experience is a strong trigger for flood precautionary behaviour (Grothmann and Reusswig, 2006; Siegrist and Gutscher, 2006, 2008; Kreibich and Thieken, 2009; Kreibich et al. 2011a; Bubeck et al., 2012a). For instance, it has been shown by Smith (1981) and Wind et al. (1999) that damage is reduced significantly if people have had frequent and recent experience of flooding. Bubeck et al. (2012c) provides an overview on the long-term development of four different types of flood mitigation measures among flood-prone households between 1980 and 2011 along the River Rhine in Germany. This long term development also shows a clear relationship between the occurrence of food events and the implementation of precautionary measures by private households. For instance, the number of implemented measures sharply increased after the severe flood event in 1993. That flood experience strongly influences the adoption of precautionary measures is also confirmed by strong correlations between the number of reported flood events per year and the number of implemented measures (Bubeck et al. 2012c).

From an economic point of view it is important that such measures are efficient and show a benefit-cost ratio larger than one (Kreibich et al. 2011b). Additionally, financial incentives can help individuals and companies to invest in self-protection. Such incentives can be provided either through appropriate insurance contracts (Kleindorfer and Kunreuther, 1999; Botzen et al., 2009; Holub and Fuchs, 2009) or else through governmental schemes or aid supporting private precautionary measures.

In line with the growing importance of flood mitigation measures in risk-based flood management concepts, there has been also a renewed interest in the factors that motivate households to undertake such measures. Initially, the literature focused on flood risk perceptions (Grothmann & Reusswig 2006) and it was commonly argued that people undertake precautionary measures to reduce a risk they perceive as being high (e.g. Plapp & Werner 2006).A review of risk perceptions and other factors that influence flood mitigation behaviour is provided by Bubeck et al. (2012a). It shows that empirical studies that have investigated the relation between flood risk perceptions and the adoption of private flood mitigation measures reveal only a weak or no statistically significant relation (e.g. Kreibich et al. 2005; Siegrist & Gutscher 2006; Takao et al. 2004; Thieken et al. 2006; Miceli et al. 2008). Several articles have addressed and discussed the reason for this weak relationship between risk perceptions and mitigation behaviour in recent years and explanations range from methodological aspects associated with cross-sectional studies to the psychological process of decision making under risk (Bradford et al., 2012; Wachinger et al., 2013; Siegrist 2013; Bubeck et al., 2012a; 2013). Moreover, a number of studies increasingly focused on other factors that could possibly drive mitigation behaviour and several studies applied variables of psychological concepts to explain decision making in response to threats, such as Protection Motivation Theory (PMT) (Grothmann and Reusswig, 2006; Bubeck et al., 2013; Koerth et al., 2013). For instance, the investigation of survey data of 752 flood-prone households along the river Rhine confirms that flood-coping appraisal, which is one component of PMT, is an important factor of influence on precautionary behaviour (Bubeck et al. 2013). Coping appraisal is comprised of three elements and refers to a respondents self-evaluation of his or her ability to implement a certain measure (self-efficacy), the belief that the respective measure is effective in preventing or reducing damage (response-efficacy) and the expected costs of that measure (Rogers 1975; 1983; Maddux and Rogers, 1983). This study reveals that both self-efficacy and response efficacy considerably influence flood mitigation behaviour, whereas response costs associated with implementing precautionary measures are mostly insignificant; with the exception of financial costs of implementing building precautionary measures, probably due to the high costs associated with this type of measure. However, results also show that while flood mitigation measures were found to be appraised positively, they are often postponed (Bubeck et al., 2013).

3.2 Damage reducing effects

Not many studies investigate the quantitative damage reducing effect of private mitigation measures, probably also due to a lack of data. However, there is some evidence that these measures are effective in reducing damage and are also often efficient (ICPR, 2002; Kreibich et al., 2005; 2011b; Olfert, 2008; Holub and Fuchs, 2008). Some studies aim to quantify the damage reducing effect of different measures at the building level (Table 1). These include scientific studies based on empirical damage data (e.g. Kreibich et al. 2005; 2009; Bubeck et al., 2013; Hudson et al. submitted) as well as practical studies based on expert judgment and/or a rather intransparent database (e.g. ICPR, 2002; ABI 2003; DEFRA, 2008). Table one shows that the spread of revealed damage reduction due to specific measures is large, which is quite clear, since the effectiveness always depends on the specific local conditions during the flood. For instance, the effectiveness of a sealed cellar is significantly reduced if the cellar must be flooded to counteract buoyancy forces (ICPR, 2002). The comparison between the more general studies (DEFRA, 2008; ICPR, 2002) and the empirical study related to an extreme event suggests, that the effectiveness of dry flood proofing is strongly reduced during an extreme event, which is not so much the case for wet flood proofing (Table 1).

Table 1 Selection of studies on damage reducing effects of precautionary measures undertaken by private households on the building level.

Measure	**Reduction**	**Source**
Wet proofing		
Flood adapted use	46-48% 30-40%	Kreibich et al., 2005 ICPR, 2002
Flood adapted interior fitting	53% 15-35% 35-45%	Kreibich et al., 2005 ICPR, 2002 DEFRA, 2008
Installation of heating and electrical utilities in higher storeys	36%	Kreibich et al., 2005
Avoidance of contamination	35-52% > 50%	Kreibich et al., 2005 ICPR, 2002
Dry proofing		
Temporary resistance, e.g. Mobile	29%	Kreibich et al., 2005

water barriers	60–80% 50%	ICPR, 2002 DEFRA, 2008
Flood adapted building structure, e.g. cellar sealing, permanent flood proof doors and windows	24% 10-85% 65-84%	Kreibich et al., 2005 ICPR, 2002 DEFRA, 2008
Building without cellar	22-24%	Kreibich et al., 2005

Further examples of scientific empirical studies are the following: Bubeck et al. (2012c) followed a repeated-measure design to compare the amount of flood damage suffered by the same households during two consecutive flood events along the German part of the Rhine in 1993 and 1995, including only these households which reported identical water levels during both flood events. The trend of lower flood damage in 1995 was attributed to a considerable increase in the implementation of private precautionary measures after 1993. Hudson et al. (submitted) applied an econometric evaluation technique called Propensity Score Matching to a survey of German households along three major rivers that were flooded in 2002, 2005 or 2006. This approach aimed at avoiding a biased estimate, which can occur if risk characteristics differ between individuals who have, or have not, implemented mitigation measures. Bias corrected effectiveness estimates of several mitigation measures show that these measures are very effective since they prevent between €6,700-14,000 of flood damage.

Furthermore, there are modeling studies that aim to estimate the damage or risk reducing effect of such measures at a regional scale (e.g. Bubeck and De Moel, 2010; Poussin et al., 2012; De Moel et al., 2014). These studies have used expert judgment and insights gained from empirical studies (like the ones listed in table 1) as input. Bubeck and De Moel (2010), for instance, look at the embanked part of the Netherlands, where large inundation depths (several meters) can occur as a result of the bathtub-like flooding of dike ring areas with low elevations. As a result, they find that dry- and wet-proofing of all existing houses would reduce flood risk by only 5.5% and 7% respectively. Poussin et al. (2012) looked at the Meuse valley in the south of the Netherlands and found a considerable higher potential there for damage-reducing measures, 10%-15% risk reduction for wet-proofing and 15%-25% reduction for dry proofing. Also in New York City a considerable potential for damage reduction has been shown (Aerts et al., 2013). Depending on the height up to which the measures are taken, the risk of buildings could be reduced by 10%-30% for wet-proofing, and 20%-50% for dry-proofing. Note that this relates only to the risk of buildings, whereas the studies of Bubeck and De Moel (2010) and Poussin et al. (2012) look at reductions on the overall risk. A high potential for damage-reducing measures has also been found for flooding in the (usually elevated) unembanked area of the Rotterdam region (De Moel et al., 2014). Here reductions in total risk of ~30% for wetproofing, and ~60% for dryproofing are found. This can be explained by the relative low inundation depths there (generally < 1m), resulting from the systematic elevation of the unembanked area to accommodate developments. This becomes even more apparent when only the flood risk to buildings is considered, which is almost completely nullified when all buildings are elevated for 1 m (De Moel et al., 2014).

Costs associated with implementing building precautionary measures have been extensively documented in the United States, but less in other countries. For instance, Aerts et al., (2013) estimated combined costs for different types of buildings for New York based on detailed costs of many different activities (FEMA, 2009; Jones et al., 2006)(Table 2). For the Netherlands, Gersonius et al. (2008) estimated aggregate costs for different types of houses (Table 2). These estimates from the USA and Netherlands illustrate that elevating an existing building is very costly (€25000), however, when implemented at the time of building, the extra costs are quite low. Both studies have similar estimates for the costs of dry proofing (around €7500 for 1m), however, estimates for wet proofing vary considerably. This is because the wet proofing in the estimates for the United States relate to the wet proofing of an unfinished basement , whereas the estimate of Gersonius et al (2008) relates to the wet proofing of the first living floor, which is much more costly (over €17000).

Whilst important, the technical cost of the measure itself is not the only consideration associated with precautionary measures. Often, such a measure involves certain adjustments to a building structure which are outside the normal building standards. This may be associated with substantial administrative paperwork, which has its cost as well. Moreover, the implementation costs can be borne by various actors. This could be the project developer, who will most likely include it in the selling price; for instance in the case of 'sustainable homes' in the United States. Costs can also be borne by a local authority (municipality, water board) who wants certain building to be adapted, or of course by the owners of a home themselves.

Table 2. Estimates of costs of damage-reducing measures at the building level. Note that the estimates of Aerts et al., (2013) are mainly based on FEMA (2009) and Jones et al. (2006).

Measure	Cost per house	Source	Country
Elevating 60cm	€ 24000 ($33000)	Aerts et al., 2013	USA
Elevating 120cm	€ 25500 ($35000)	Aerts et al., 2013	USA
Elevating 180cm	€ 27000 ($37000)	Aerts et al., 2013	USA
Elevating 60cm (new)	€ 1800 ($2500)	Aerts et al., 2013	USA
Elevating 120cm (new)	€ 3650 ($5000)	Aerts et al., 2013	USA

Elevating 180cm (new)	€ 5500 ($7500)	Aerts et al., 2013	USA
Wet proofing 60cm	€ 1600 ($2150)	Aerts et al., 2013	USA
Wet proofing 120cm	€ 3250 ($4450)	Aerts et al., 2013	USA
Wet proofing 180cm	€ 6200 ($8500)	Aerts et al., 2013	USA
Dry proofing 60cm	€ 6100 ($8300)	Aerts et al., 2013	USA
Dry proofing 120cm	€ 7600 ($10400)	Aerts et al., 2013	USA
Dry proofing 180cm	€ 9200 ($12600)	Aerts et al., 2013	USA
Elevate column 50cm	1200	Gersonius et al., 2008	NL
Elevate column 100cm	1900	Gersonius et al., 2008	NL
Elevate wall 30cm	2000	Gersonius et al., 2008	NL
Elevate wall 60cm	3100	Gersonius et al., 2008	NL
Elevate wall 90cm	4300	Gersonius et al., 2008	NL
Wet proofing 100cm	17700	Gersonius et al., 2008	NL
Dry proofing temp. 90cm	2300	Gersonius et al., 2008	NL
Dry proofing perm. 90cm	7600	Gersonius et al., 2008	NL
waterproof cellar using a bitumen sealing	465.10 €/m²	Kreibich et al. 2011b	GER
waterproof cellar using waterproof concrete	505.00 €/m²	Kreibich et al. 2011b	GER
mobile water barrier (1m x 1m)	610 €	Kreibich et al. 2011b	GER
floodproofed oil tank with a volume of 1500 litres	1009 €	Kreibich et al. 2011b	GER

Implementing a precautionary measure is economically beneficial, if the aggregated benefits (damage reduction) outweigh the costs (investment and maintenance costs) over the calculation period or life-time of the measure. Some cost-benefit analyses have been undertaken: For example, Holub and Fuchs (2008) investigate the cost-effectiveness of mitigation measures and regard a measure as effective if benefits are larger than costs. Holub and Fuchs (2008) estimate the natural hazard risk posed in their sample area. Once the level of risk is known, the sample area is divided into different risk zones and the level of exposure within a risk band is used to estimate damages. Holub and Fuchs (2008) then proceed to calculate the benefits of the measures by assuming that a precautionary measure prevents all damage up to a certain severity of hazard. Kreibich et al. (2011b) follow a micro-economic approach on household level, which reveals that mainly small investments like the installation of an oil tank protection can prevent high damage at very low cost and are as such particularly efficient.

4. Conclusions

Empirical studies and model results suggest a high potential for flood risk mitigation via integrated approaches to flood risk management including spatial planning and private precautionary measures. Damage-reducing measures will gain even more importance given the increase in flood risk due to climate change as well as an increase in vulnerability that is due to increasing flood plain occupancy, value increase in endangered areas and changes in the terrestrial system like land cover changes. These socio-economic changes can be significantly influenced maybe even adjusted using spatial planning including building codes and private damage reduction measures. However, despite the fact that spatial zoning and land use planning are part of risk management in many countries, their effectiveness in flood risk mitigation is often low. Similarly, the contribution of private flood damage reduction has become an integral component of contemporary flood risk management in many countries, but many flood endangered households and companies still don't undertake any precautionary measure. Therefore, further efforts are required to increase the effectiveness of damage-reducing measures, via better cooperation between all stakeholders, improved risk communication, (financial) incentives or stricter legal regulations.

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