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Research article

The benefits of flood mitigation strategies: effectiveness of integrated protection measures

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Abstract: Given the investments that local, regional, and national governments have already made in mitigation and may consider in the future, it is crucial to assess mitigation effectiveness across all scales and determine which strategies are the most appropriate. This is particularly relevant as mitigation is viewed increasingly as a vital action for which investments and the resulting benefits must be evaluated and justified. It is fundamental to determine which measures are the most effective in optimising the response to floods in local communities.

The study analyses the current state of knowledge on flood mitigation and reviews what methodologies have been applied in order to assess mitigation effectiveness and positive cost-benefit ratio (CBR). The growing body of literature has shown that losses from natural hazards can be significantly reduced when one or more mitigation techniques are put into practice.

Moreover, an effective response to floods requires the contribution of flood-prone households and their local community, known as the bottom-up approach, in order to apply risk management strategies to increase community resilience. The results demonstrate that effectiveness increases when integrated approaches are implemented. In particular, the combination of top-down and bottom-up solutions can provide the best results in terms of socio-economic assessments.

The study found that the commitment of both public and private stakeholders was of vital importance in achieving good flood mitigation levels, thus, mitigation must be seen as a joint effort between these actors. The paper also provides key findings from literature and recommendations for further research.

Keywords: flood mitigation strategies; mitigation benefits; integrated mitigation measures; private mitigation; risk perception

1. Introduction

Nowadays, we are seeing a major increase in the potential impact from river and coastal flooding, which is caused by both current and future socio-economic and climate changes [1,2]. In fact, climate change is expected to increase the frequency and severity of natural hazards [3,4]. Economic growth will generate new exposure to people and assets concentrated in cities, which are often situated in vulnerable locations. Consequently, risk will increase due to the simultaneous rise of all its components: exposure, hazard and vulnerability [5]. This will cause a negative impact on communities, economies and ecosystems [6,7]. Therefore, it is clear that policymakers, as well as local stakeholders, must put a stronger emphasis on risk-reduction measures, which are necessary to impede an increase in loss [3,8,9].

While the need to understand how to develop efficient disaster mitigation options and actions is becoming increasingly urgent, no common definition of "mitigation" actually exists. In its report on "Cost and Benefits of Natural Hazard Mitigation" (1997), the US Federal Emergency Management Agency (FEMA) defines mitigation as "a sustained action taken to reduce or eliminate the long-term risk to people and property from natural hazards and their effects". This delineates a difference between mitigation and other major emergency management actions, such as preparedness, response and short-term recovery [10].

Generally, mitigation is interpreted only as "prevention" in the "*prevention, preparedness, response and recovery continuum of emergency management*" [11]. For example, Ganderton [12] affirms that "*most mitigation involves employing resources in advance of a disaster to reduce subsequent losses*", as well as Lindell and Prater [13], who define it as "*preimpact actions that protect passively against casualties and damage at the time of hazard impact (...) and include community protection works, land use practices, and building construction practices*".

However, we can affirm that mitigation involves more than just hazard prevention and pre-impact activities and has been proven to be crucial to improving community resilience. For instance, actions performed during response phases could be useful to both reduce further possible consequences and increase the speed of post-event recovery.

This paper uses "mitigation" to refer to any activity or procedure that is implemented before and during a flood, so that the impact of or loss caused by the event can be predicted and avoided or reduced.

In the past, mitigation interventions relied primarily on flood containment through the construction of structural measures. The risk-mitigation approach was mainly monodisciplinary and focused on hazard reduction actions. Flood management has now shifted from protection against flooding to managing flood risk, thanks to various changes taking place at the social level [14]. For example, the European Commission Floods Directive 2007/60/EC asked member states to draw up maps and plans for flood risk management and create measures for prevention, protection and preparedness [15,16]. Therefore, the most appropriate and effective mitigation interventions must be identified and prioritised [17]. Then, the benefits of these measures over the long-term must be assessed prior to choosing the most effective set of strategies to manage flood risk [18].

Investing in mitigation activities can save money and lives. An economic assessment of disaster risk reduction is usually based on cost benefit analysis (CBA), which is an established economic tool to identify and compare all costs incurred and benefits resulting from mitigation measures [19–21]. CBA is applied in four phases: (1) define the project; (2) allocate resources; (3) identify project impacts; (4) assess potential benefits. Mitigation is found to be effective and economically acceptable based primarily on cost-benefit ratios (CBRs). If the benefits exceed the costs, then it is justifiable to invest in mitigating flood risk [19]. However, it is still unclear which type of mitigation measures increase community resilience and if they are economically efficient. This study aims to: assess current approaches to economic efficiency assessment in natural hazard risk management; classify several current studies on mitigation actions based on strategies adopted; identify which mitigation measures are effective in reducing or preventing impact and loss from flood disasters; analyse the involvement of individuals and local stakeholders in the mitigation process. Most local, regional and national flood risk management plans include the implementation of structural (i.e. reservoirs, dams, dikes and levees) and non-structural (i.e. land use policy, early warning, property level flood risk mitigation measures, financial incentives and risk transfer) flood alleviation schemes [22,23]. Consequently, individual households have taken on a more prominent role in managing flood risk [24–26].

Private mitigation measures and individual property protections decrease the vulnerability of resident assets in flood-prone areas. Lack of physical protections, residual risk, negative mitigation CBR, bottom-up initiatives and financial incentives may encourage households to undertake mitigation measures [27]. However, the two key variables to be considered are the way individuals perceive risk and their hazard knowledge. These influence whether people respond to flood risk by adapting to, coping with or ignoring it. The role of risk perception can trigger behavioural changes to increase community resilience. The decision of households to intervene privately in flood mitigation can strengthen the effectiveness of implemented public measures.

2. Methodological approaches to assess benefits from mitigation measures

Firstly, to analyse the most effective flood mitigation strategies, a list of the various categories of existing flood mitigation measures must be made. Hereinafter, they are classified according to their sources: United Nations [28], UNISDR [29], Bouwer et al. [30] and Newman et al. [11]. The classification is based on different categories of mitigation, their objectives and their methodological approaches. Mitigation measures can be divided by their nature, such as structural measures (e.g. dams, retention basins, etc.) or non-structural measures (e.g. land-use planning, communication strategies, monitoring, early warning systems and emergency response, financial incentives, and risk transfer, as well as private measures regarding residential and non-residential buildings).

Moreover, these categories can be grouped according to their main goals: hazard mitigation, loss mitigation or impact mitigation. Infrastructures and other technical solutions function through hazard reduction. Other categories impact on vulnerability, as flood loss is not only related to hazard severity but also depends on the response to natural hazards. While they do not mitigate hazard, communication, monitoring, early warning systems and emergency response measures can reduce loss through improvement of response capability and then reduction of the long-term social impact of a flood [11]. Similarly, a common measure to improve recovery is through insurance.

In this section, key examples and issues related to assessment of mitigation measures are given. Private flood mitigation, insurance and integrated methods are also explored as strategies that can be implemented in addition to public measures.

2.1. Infrastructure

Jeuken et al. [31] model monetary costs and benefits of four strategies that protect the Rotterdam area until 2100. These strategies range from an open estuary with strong dikes to a closed estuary defended by dams and locks. While the applied strategies are beneficial for Rotterdam and nearby cities, they are believed to have severe negative impacts along the rivers further upstream.

Kind [32] calculates economically efficient flood protection standards for the Netherlands using a specific CBA methodology. He proposes economically efficient flood protection standards that are remarkably more efficient than the existing ones.

Kousky and Walls [33] use a GIS to evaluate flood damage reduction strategy by means of floodplain conservation, considering the co-benefits that protected lands provide. They assess the investment of a greenway along the Meramec River in Missouri by estimating opportunity costs, avoided flood damage and benefits that are capitalised into house prices in a five-mile surrounding area. The study demonstrates that increased property values for houses near protected lands are three times higher than the avoided flood damage.

In general, studies show that building flood protection infrastructures is exorbitantly expensive and implicates long-term costs, although it is often characterised by a high CBR.

2.2. Land-use planning

Land-use management and zoning plans are designed to manage agricultural land and limit construction of new buildings in flood-prone areas. Policymakers prefer planning tools for risk mitigation, as they can be applied at local, regional and national levels [27,30].

In one of the case studies cited in its report, FEMA [10] delineates its land-use and building requirements in floodplains, which are included in the National Flood Insurance Program (NFIP). The Program envisages the integration of mitigation strategies into both local land-use planning and building design. Since 1975, over two million buildings have been constructed in flood-prone areas that were part of the NFIP. In the period between 1978 and 1995, flood insurance policies generated a surplus of 169 million dollars for the National Flood Insurance Fund, demonstrating the effectiveness of the NFIP.

Muis et al. [8] analyse two mitigation strategies to deal with climate change in Indonesia. The dataset covers future trends up to 2030 and includes urban expansion and potential river and coastal floods in the model. The results show that, by following a strict spatial planning strategy, potential loss can be reduced by 33% for river floods and 65% for coastal floods, if policymakers choose a low protection level. However, if the policy opts for a high level, the potential reductions are 93% for river floods and 95% for coastal floods.

Koks et al. [34] illustrate the benefits of land-use zoning in the coastal area of Belgium which is expected to generate about a 15–20% reduction in loss.

A further aspect that must be considered is assessment of intangible costs, which may relate to health, cultural or environmental impacts that cannot be monetarily calculated. In these cases, people may accept compensation in exchange for tolerating a certain amount of discomfort [35].

2.3. Communication

Assessment of communication and preparedness campaigns considers the operational costs of communication campaigns, preparedness training, websites, media and other means of communication. Only few studies have tried to estimate this category of costs.

Haer et al. [36] evaluate several flood risk communication strategies and affirm that communication campaigns do not always result in the expected action. They suggest that tailored and people-centred flood risk communication can be much more helpful compared to the usual top-down approach managed by policymakers and s that the most effective means to disseminate flood risk communication are social networks.

Boyd [37] analyses the success of disaster preparedness training for the City of Bellingham, Washington. The author surveyed city employees after the training. The results show that 76% took some form of disaster preparedness action after attending the session, which was mainly discussing preparedness with family members.

2.4. Monitoring and early warning systems

Monitoring and early warning strategies are expensive primarily due to their implementation costs (e.g., engineering, investments and maintenance costs). The European Union's Global Monitoring for Environment and Security programme of standardised data collection [38] cost approximately €4 billion from 2014 to 2020.

Hallegatte [1] applies hypotheses derived from other studies [39–41] and estimates that hydro-meteorological information and early warning systems can save hundreds of lives and from €460 million to €2.7 billion in Europe every year. Moreover, they can generate extra benefits worth between €3.4 and €34 billion for economic sectors that are sensitive to weather changes. As some of the most expensive early warning systems already exist (e.g., earth observation satellites, weather forecast systems), investments in this sector are low (about one billion USD per year) and have a CBR between 4 and 36.

Pappenberger et al. [42] calculate the monetary benefit of early flood warnings in Europe through the use of flood damage cost information and calculations of avoidable flood damages. The estimated benefits are approximately €400 for every €1 invested.

Molinari et al. [43] present a method to assess the effectiveness of early warning in reducing physical damage caused directly by flash floods and compare benefits and emergency management costs, considering various scenarios. The results show a significant reduction in the percentage of potential damage.

In order to assess the benefits to people of early warning for urban flood risk, Balbi et al [44] study the Sihl River catchment case study in Switzerland. Results indicate that an improved early warning can avoid human impact, particularly in case of a major flood event: about 75% of fatalities, 25% of injuries and 18% of post-traumatic stress disorders can be avoided.

2.5. Emergency response

Very few studies have attempted to assess the costs and effectiveness of emergency response and evacuation. Penning-Rowsell et al. [45] and Penning-Rowsell and Wilson [14] analyse data from floods that occurred in the U.K. in 2000 and apply a fixed value of 10.7% to property loss, as an estimate of the emergency response cost, which includes costs for police, fire and ambulance interventions, the local authority and the Environmental agency.

De Jong and Helsloot [46] describe a simulation that was held to recreate a large-scale evacuation involving about 10,000 participants in response to a flood event in the Netherlands. The cost of the simulation is assessed at 3 million.

Pfurtscheller and Thieken [47] analyse the costs of emergency management in four Alpine regions and calculate the annual expenses of flood protection in these areas. Using data from past river floods in Austria and Germany, they find that 10 to 12 per cent of all direct loss can serve as an estimate to assess emergency costs for floods.

Bachner et al. [48] estimate the potential benefits of voluntary emergency management services in Austria. The benefits range from €0.22 to €1.09 billion in salary savings, €0.04 to €0.32 billion in mental health support, €0.02 to €5.89 billion in social capital benefits, and €0.15 billion in benefits for private households.

2.6. Financial incentives and risk transfer

Financial incentives encourage households and private businesses to take measures to protect their properties. Different forms of risk transfer exist and their costs are variable and related to the level of coverage. A risk transfer scheme can be set up before (ex-ante) or after (ex-post) a flood event [49].

One of the most common ways to improve disaster recovery is through insurance. Insurance does not reduce loss or hazard but improves recovery capability and guarantees that money is available during the recovery phase. Insurance helps to mitigate disaster loss in local regions and to modify people's behaviour, as it encourages landowners to reduce their vulnerability privately in order to lower their insurance premium [50]. However, insurance can be unhelpful by encouraging construction in at-risk areas [11].

Growing attention is being paid to the role insurance can play in mitigating damage by encouraging policymakers to undertake protection measures. Botzen et al. [51] used a survey to investigate the willingness of homeowners in the Netherlands to invest in flood mitigation interventions when benefits to potential flood insurance policies were offered. The results indicate that more than 60% of homeowners were willing to build water barriers, 20% were willing to buy water resistant flooring, and 25% were willing to move heating installations to higher floors. The results indicate that these measures are highly effective and can prevent damage worth approximately €1 billion.

Hudson et al. [52] show how insurance-based incentives are able to promote mitigation and can reduce residential flood risk by 12% in Germany and 24% in France by 2040.

2.7. Integrated approach

Effective flood risk mitigation requires combined approaches to intervention. Integrated and targeted mitigation interventions have proven to reduce flood impact over time [9]. To deal with the potential increase in flood risk, several studies recommend a combination of structural and non-structural mitigation measures as an effective mitigation strategy.

While public authorities are less likely to finance traditional infrastructures, such as dams and retention basins, due to the economic crisis, several recent studies demonstrate the positive effects of implementing integrated protection measures at the local level. For example, Holub and Fuchs [53] assess benefits of local structural protection to mitigate torrent-related hazards in Carinthia, Austria. A standardised CBA method is applied to obtain the cost-efficiency of these mitigation measures, showing that they significantly reduce the hazard.

Brouwer and van Ek [54] integrate environmental, economic and social impact assessments to support policymaking in the Netherlands. Even if the resulting CBA indicates that the traditional flood control policy (i.e., use of dikes) is the country's most cost-effective option, investments in land-use changes and floodplain restoration are economically justifiable in the long term. Benefits include public safety, creation of new wildlife habitats and amenity values.

Alfieri et al. [55] analyse four different mitigation strategies: (1) current flood alleviation defences, (2) flood storage and retention areas, (3) non-structural measures, such as early warning, dry and wet proofing, and (4) relocation. The authors calculate the benefits of the four strategies considering various scenarios on a European level. Results indicate that the traditional structural defences are less efficient than the other three strategies, primarily because of the “levee effect”.

De Moel et al. [56] assess the benefits of five different risk management options (area elevation, building elevation, dry proofing, wet proofing and warning/communication) to mitigate flood risk in Rotterdam, considering six different scenarios and return periods. The results show that, up to 2100, expected loss can be reduced by using dry proofing or building elevation. Whereas flood warning has a limited effect on risk in the area.

Lasage et al. [57] analyse the benefits of different mitigation strategies for one district of Ho Chi Minh City (Vietnam). They show that wet- and dry-proofing provide benefits from 20% to 95%. Moreover, an increase in protection elevation (about 2.11 m) can generate a risk reduction of 100%. Other potential scenarios, such as dike construction, show no benefit increase.

3. Private mitigation

Recent studies consider private flood mitigation as a strategy that can be implemented in addition to public measures, as public protection cannot completely eliminate the risk of flooding. Thus, property-level mitigation measures, which proactively protect homes from flooding or reduce resulting damage, are an essential part of modern flood risk management. In fact, as public flood defence systems can fail, private mitigation may be vital to reducing residual damage [23].

With regards to the flooding of the Elbe and Danube in 2002, Thieken et al. [58,59] and Kreibich [60,61] used surveys to demonstrate the fundamental importance of private intervention. In particular, in 2006, Thieken et al. [58] used insurance surveys to identify eligibility conditions for changes to flood insurance in Germany after the 2002 event. The article analyses flood loss compensation, risk awareness, and mitigation in insured and uninsured private households. The study results demonstrated that appropriate incentives and flood insurance should be combined in order to build an integrated approach to support future private flood loss mitigation.

According to Kreibich et al. [60], flood loss can be effectively mitigated only by improved flood risk management, which includes interventions undertaken by private households. These involve a range of financially "reasonable" efforts that households put in place to self-insure and self-protect, prior to receiving support from publicly funded relief programmes. Interviews with single-family homeowners were conducted in flood catchments areas in Germany after the events of 2002, 2005 and 2006 and market-based cost assessments were modelled. In general, the CBR showed that large investments were economically efficient only when buildings were frequently flooded. Small investments were more advantageous if buildings were flooded every 50 years. The study also showed that 31% of the population in flooded areas had implemented preventive measures, which included moving possessions to their second floor (implemented by over 50%), protecting documents and valuables, relocating vehicles, disconnecting electricity and gas supplies and installing water pumps.

Sairam et al. [62] quantitatively calculated vulnerability reduction in Germany through employment of private precautionary measures. They provided strong evidence that implementing private preventive measure reduced residential building loss by an average treatment effect of €11,238 to 15,053.

Therefore, local structural interventions significantly reduce building vulnerability to natural hazards and should always be implemented as an additional or alternative mitigation measure [53]. However, property-level flood mitigation interventions are limited by the fact that they are implemented primarily on the basis of individual experience and perception [27].

Since these are basically low-cost measures, it can be hypothesised that they should be made mandatory when implementing building codes. Policymakers should introduce financial incentives into insurance contracts that provide economic motivation for households to invest in precautionary measures [60], for example, encouraging people to reduce their vulnerability in order to lower their insurance premium [11].

3.1. Individual risk perception

Homeowners are driven by a variety of reasons when dealing with flood risk. These may include: financial incentives; hydrogeological or geomorphological issues preventing public mitigation actions; engineering issues, such as residual risk failure; legislative and/or economic reasons, e.g. negative cost/benefit ratio for large-scale interventions [27].

Private mitigation measures can reduce the impact of flood events [63]. These may include redesigning the surrounding area to drain waters, constructing on elevated ground, raising existing buildings or constructing new amphibious or floating structures. Less expensive interventions may include applying wet or dry proofing or the use of permanent or mobile barriers to stop the passage of water [27]. In many cases, even small changes can protect buildings against flooding and effective measures can be integrated into the construction of new homes.

Designing integrated risk management strategies requires accurate knowledge of the exposed area. The way in which communities and individuals perceive risk and react to it is a significant hindrance that cannot be underestimated. To correctly assess risk and mitigation tools, it is crucial to consider how people may behave, their willingness to act individually and their access to information [36].

Property-level flood risk mitigation measures are often built on the basis of individual experience and perception [63] and are, thus, largely voluntary. Therefore, they require self-responsibility on the part of people affected to be implemented [23]. However, there is a lack of knowledge on the need for and usefulness of private mitigation measures and, so, they are inadequately implemented [59]. It is debatable that low-cost interventions should be made mandatory within existing building codes. This could happen if government programmes were able to motivate households to invest in mitigation measures through the introduction of financial incentives [60], for example, encouraging people to reduce their vulnerability in order to lower their insurance premium [11].

Self-efficacy in preventing and responding to risk events depends on how people perceive their safety [64]. Their willingness to invest in prevention is specifically related to their age, level of education, type of community and proximity to water [24,26]. There are various theoretical concepts regarding risk perception and its resulting behaviour, such as the Protective Action Decision Model (PADM) developed by Lindell and Perry [65], Protection Motivation Theory (PMT) by Rogers [66,67], and Societal Amplification of Risk Framework (SARF) by Kasperson et al. [68]. These studies focus on cognitive, socio-economic and situational elements, with the aim of understanding individual motivations. Such theories use a wide range of variables to explain why individuals take or do not take protective actions. The main variables considered in recent studies include socioeconomic (e.g. age, gender, income) and cognitive (knowledge, responsibility) factors or are linked to personal experience, such as having suffered previous flood events [69,70] combined with objective risk factors such as geographical location [71].

4. Conclusions

In recent years, a growing body of literature has tried to estimate flood costs, while only a few studies have actually looked at the benefits of mitigation in terms of loss prevention [47].

It is important to understand that evaluating flood mitigation is a complex task, which is influenced by several variables. For example, while some disaster costs are measurable in monetary terms (direct costs), others do not have a market value and are difficult to quantify (indirect and intangible costs) [30].

Another aspect that must be recognised is that natural hazards have a total effect on the communities they hit, including their individuals, businesses and public services. A flood event can generate ripple-effects on the community and, consequently, increase the number of variables that must be considered [10].

If conducted correctly, a CBA is a sound method of evaluating and comparing projects. It helps decision-makers choose between various mitigation options and provides a means to assess how public funds are to be spent. However, mitigation measures do not necessarily or inevitably have a favourable CBR. As well, the fact that a disaster may never occur must also be taken into consideration. For instance, Shreve and Kelman [19] wondered if it was worth assessing flood mitigation measures if they were taken within a property that has never suffered a flood.

Several studies affirm that large investments are economically sound only if the area in question is frequently flooded. Small investments, which are primarily undertaken by homeowners, are more advantageous when buildings are rarely flooded. Most recent studies have hypothesized an integrated approach that envisages a combination of the mitigation interventions described above. Among technical interventions, some measures are on such a small scale that they can implemented by homeowners or local communities. This analysis also highlights the need to take human behaviour into consideration when implementing mitigation actions to better respond to flood risk. Factors that guide individual perception of risk and local adaptive capacities need to be investigated to better manage mitigation approaches at all levels.

Moreover, flood mitigation strategies cannot be limited to building infrastructures or developing plans through a top-down approach. Local governments and decision-makers must adopt integrated risk management strategies, which can be significantly more effective when local communities are involved. A participatory approach in flood risk management should consider risk mitigation as a common effort between public and private actors. This approach must include investment in communication and knowledge, as they are the basis of the prevention process through public participation and education initiatives [72].

In the prevention phase, social trust can accelerate the decision-making process and increase risk awareness. The commitment of stakeholders and end-users has proven to be of vital importance in achieving good mitigation levels, rendering citizens and economies more resilient against future events.

Conflict of interest

All authors declare no conflicts of interest in this paper.

References:

1. Hallegatte S (2012) A cost effective solution to reduce disaster losses in developing countries hydro-meteorological services, early warning, and evacuation. *Policy Research Working Paper*, 6058, World Bank, Washington, DC.
2. Osberghaus D (2014) The Determinants of Private Flood Mitigation Measures in Germany—Evidence from a Nationwide Survey. *Ecol Econ* 110: 36–50.
3. Aerts JCJH, Botzen WWJ, de Moel H, et al. (2013) Cost estimates for flood resilience and protection strategies in New York City. *Ann N Y Acad Sci* 1294: 1–104.
4. Genovese E, Green C (2015) Assessment of storm surge damage to coastal settlements in Southeast Florida. *J Risk Res* 18: 407–427.
5. Lugeri N, Kundzewicz ZW, Genovese E, et al. (2010) River flood risk and adaptation in Europe—assessment of the present status. *Mitigation Adapt Strategies Global Change* 15: 621–639.
6. IPCC (2014) *Climate Change 2014. Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects*. In Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, USA.
7. IPCC (2014) *Climate Change 2014. Mitigation of Climate Change*. In Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, USA.
8. Muis S, Güneralp B, Jongman B, et al. (2015) Flood risk and adaptation strategies under climate change and urban expansion: A probabilistic analysis using global data. *Sci Total Environ* 538: 445–457.
9. Jongman B (2018) Effective adaptation to rising flood risk. *Nat Commun* 9: 1–3.

10. FEMA (1997) *Report on Costs and Benefits of Natural Hazard Mitigation*, Hazard Mitigation Technical Assistance Program.
11. Newman JP, Maier HR, van Delden H, et al. (2014) *Literature review on decision support systems for optimising long-term natural hazard mitigation policy and project portfolios*. The University of Adelaide, Report N. 2014.009.
12. Ganderton PT (2005) Benefit–cost analysis' of disaster mitigation: application as a policy and decision-making tool. *Mitigation Adapt Strategies Global Change* 10: 445–465.
13. Lindell MK, Prater CS (2003) Assessing Community Impacts of Natural Disasters. *Nat Hazards Rev* 4: 176–185.
14. Penning-Rowsell E, Wilson T (2006) Gauging the impact of natural hazards: The pattern and cost of emergency response during flood events. *Trans Inst Brit Geogr* 31: 99–115.
15. Santato S, Bender S, Schaller M (2013) The European Floods Directive and Opportunities offered by Land Use Planning. CSC Report 12, Climate Service Centre, Germany.
16. Nones M (2017) Flood hazard maps in the European context. *Water Int* 42: 324–332.
17. Denton F, Wilbanks TJ, Abeysinghe AC, et al. (2014) Climate-resilient pathways: adaptation, mitigation, and sustainable development. *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects*. Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, 1101–1131.
18. CIS Floods Working Group (2012) Flood Risk Management, Economics and Decision Making Support. Working Group F of the Common Implementation Strategy for the Water Framework Directive.
19. Shreve CM, Kelman I (2014) Does Mitigation Save? Reviewing cost-benefit analyses of disaster risk reduction. *Int J Disaster Risk Reduct* 10: 213–235.
20. Vorhies F (2012) The economics of public sector investment in disaster risk reduction. A working paper based on a review of the current literature prepared for the United Nations International Strategy for Disaster Reduction (UNISDR).
21. Benson C, Twigg J (2004) *Measuring mitigation methodologies for assessing natural hazard risks and the net benefits of mitigation—a scoping study*. International Federation of Red Cross and Red Crescent Societies/the ProVention Consortium, Geneva.
22. Meyer V, Becker N, Markantonis V, et al. (2013) Assessing the Costs of Natural Hazards - State-of-the-art and Knowledge Gaps. *Nat Hazards Earth Syst Sci* 13: 1351–1373.
23. Kreibich H, Bubeck P, Van Vliet M, et al. (2015) A review of damage-reducing measures to manage fluvial flood risks in a changing climate. *Mitigation Adapt Strategies Global Change* 20: 967–989.
24. Bamberg S, Masson T, Brewitt K, et al. (2017) Threat, coping and flood prevention—A meta-analysis. *J Environ Psychol* 54: 116–126.
25. Paton D (2018) Disaster risk reduction: Psychological perspectives on preparedness. *Aust J Psychol* 71: 327–341.
26. van Valkengoed AM, Steg L (2019) Meta-analyses of factors motivating climate change adaptation behaviour. *Nat Clim Change* 9: 158–163.
27. Attems MS, Thaler T, Genovese E, et al. (2020) Implementation of property level flood risk adaptation (PLFRA) measures: choices and decisions. *WIREs Water* 7: e1404.

28. United Nations (1994) Yokohama strategy and plan of action for a safer world: Guidelines for natural disaster prevention, preparedness, and mitigation. In World Conf. on Natural Disaster Reduction, UN Dept. for Humanitarian Affairs, Geneva, Switzerland.
29. United Nations Office for Disaster Risk Reduction (UNISDR) (2009) Global Assessment Rep. on Disaster Risk Reduction. United Nations Inter-Agency Secretariat of the International Strategy for Disaster Reduction (UN/ISDR), Geneva, Switzerland.
30. Bouwer LM, Papyrakis E, Poussin J, et al. (2014) The Costing of Measures for Natural Hazard Mitigation in Europe. *Nat Hazards Rev* 15: 04014010.
31. Jeuken A, Kind J, Slootjes N, et al. (2013) Cost-benefit analysis of flood risk management strategies for the Rhine-Meuse delta. In Klijn F, Schweckendiek T (eds), *Comprehensive Flood Risk Management*, Taylor & Francis Group.
32. Kind JM (2014) Economically efficient flood protection standards for the Netherlands. *J Flood Risk Manage* 7: 103–117.
33. Kousky C, Walls M (2014) Floodplain conservation as a flood mitigation strategy: Examining costs and benefits. *Ecol Econ* 104: 119–128.
34. Koks EE, Bočkarjova M, de Moel H, et al. (2015) Integrated Direct and Indirect Flood Risk Modeling: Development and Sensitivity Analysis. *Risk Anal* 35: 882–900.
35. Brouwer R, Schaafsma M (2013) The economics of flood disaster management in the Netherlands. In Guha Sapir D, Santos I, Borde A, (Eds.), *The economic impacts of natural disasters*, Oxford University Press, Oxford, U.K.
36. Haer T, Wouter Botzen WJW, Aerts JCJH (2016) The effectiveness of flood risk communication strategies and the influence of social networks—Insights from an agent-based model. *Environ Sci Policy* 60: 44–52.
37. Boyd WJ (2001) *Measuring the effectiveness of disaster preparedness training for the city of Bellingham, Washington*. National Fire Academy.
38. European Commission (2008) Assessing the potential for a comprehensive community strategy for the prevention of natural and manmade disasters. Final Report.
39. Carsell KM, Pingel ND, Ford DT (2004) Quantifying the benefit of a flood warning system. *Nat Hazard Rev* 5: 131–140.
40. Barredo JI (2009) Normalised flood losses in Europe: 1970–2006. *Nat Hazards Earth Syst Sci* 9: 97–104.
41. Strobl E (2011) The Economic Growth Impact of Hurricanes: Evidence from U.S. Coastal Counties. *Rev Econ Stat* 93: 575–589.
42. Pappenberger F, Cloke HL, Parker DJ, et al. (2015) The monetary benefit of early flood warnings in Europe. *Environ Sci Policy* 51: 278–291.
43. Molinari D, Ballio F, Menoni S (2013) Modelling the benefits of flood emergency management measures in reducing damages: a case study on Sondrio, Italy. *Nat Hazards Earth Syst Sci* 13: 1913–1927.
44. Balbi S, Villa F, Mojtahed V, et al. (2015) A spatial Bayesian network model to assess the benefits of early warning for urban flood risk to people. *Nat Hazards Earth Syst Sci Discuss* 3: 6615–6649.
45. Penning-Rowsell E, Johnson C, Tunstall S, et al. (2005) *The benefits of flood and coastal risk management: A manual of assessment techniques*. Flood Hazard Research Centre, Middlesex University Press, London, U.K.

46. De Jong M, Helsloot I (2010) The effects of information and evacuation plans on civilian response during the Dutch national flooding exercise 'Waterproef'. *Procedia Eng* 3: 153–162.
47. Pfurtscheller C, Thieken AH (2013) The price of safety: costs for mitigating and coping with Alpine hazards. *Nat Hazards Earth Syst Sci* 13: 2619–2637.
48. Bachner G, Seebauer S, Pfurtscheller C, et al. (2016) Assessing the benefits of organized voluntary emergency services. *Disaster Prev Manage* 25: 298–313.
49. Warner K, Ranger N, Surminski S, et al. (2009) Adaptation to climate change: Linking disaster risk reduction and insurance. United Nations International Strategy for Disaster Reduction, Geneva, Switzerland.
50. Burby RJ (1998) Natural Hazards and Land Use: An Introduction. In Burby RJ, *Cooperating with Nature: Confronting Natural Hazards with Land Use Planning for Sustainable Communities*. Joseph Henry Press: Washington, D.C.
51. Botzen WJW, Aerts JCJH, van den Bergh JCJM (2009) Willingness of homeowners to mitigate climate risk through insurance. *Ecol Econ* 68: 2265–2277.
52. Hudson P, Botzen WJW, Feyen L, et al. (2016) Incentivising flood risk adaptation through risk based insurance premiums: Trade-offs between affordability and risk reduction. *Ecol Econ* 125: 1–13.
53. Holub M, Fuchs S (2008) Benefits of local structural protection to mitigate torrent-related hazards. In: Brebbia CA, Beritatos E, (Eds.), *Risk Analysis VI: Simulation and Hazard Mitigation.* WIT Press: Southampton, U.K., 401–411.
54. Brouwer R, van Ek R (2004) Integrated ecological, economic and social impact assessment of alternative flood control policies in the Netherlands. *Ecol Econ* 50: 1–21.
55. Alfieri L, Feyen L, Di Baldassarre G (2016) Increasing flood risk under climate change: a pan-European assessment of the benefits of four adaptation strategies. *Clim Change* 136: 507–521.
56. De Moel H, van Vliet M, Aerts JCJH (2014) Evaluating the effect of flood damage-reducing measures: a case study of the unembanked area of Rotterdam, the Netherlands. *Reg Environ Change* 14: 895–908.
57. Lasage R, Veldkamp TIE, de Moel H, et al. (2014) Assessment of the effectiveness of flood adaption strategies for HCMC. *Nat Hazards Earth Syst Sci* 14: 1441–1457.
58. Thieken AH, Petrow T, Kreibich H, et al. (2006) Insurability and mitigation of flood losses in private households in Germany. *Risk Anal* 26: 383–395.
59. Thieken AH, Kreibich H, Müller M, et al. (2007) Coping with floods: Preparedness, response and recovery of flood-affected residents in Germany in 2002. *Hydrol Sci J* 52: 1016–1037.
60. Kreibich H, Christenberger S, Schwarze R (2011) Economic motivation of households to undertake private precautionary measures against floods. *Nat Hazards Earth Syst Sci* 11: 309–321.
61. Kreibich H, Thieken AH, Petrow T, et al. (2005) Flood loss reduction of private households due to building precautionary measures—lessons learned from the Elbe flood in August 2002. *Nat Hazards Earth Syst Sci* 5: 117–126.
62. Sairam N, Schröter K, Lüdtke S, et al. (2019) Quantifying flood vulnerability reduction via private precaution. *Earth's Future* 7: 235–249.
63. Holub M, Hübl J (2008) Local protection against mountain hazards—state of the art and future needs. *Nat Hazards Earth Syst Sci* 8: 81–99.

64. Thaler T, Seebauer S (2019) Bottom-up citizen initiatives in natural hazard management: Why they appear and what they can do? *Environ Sci Policy* 94: 101–111.
65. Lindell MK, Perry RW (2012) The Protective Action Decision Model: theoretical modifications and additional evidence. *Risk Anal* 32: 616–632.
66. Rogers RW (1975) A Protection Motivation Theory of fear appeals and attitude change. *J Psychol* 91: 93–114.
67. Rogers RW (1983) Cognitive and physiological processes in fear appeals and attitude change: a revised theory of protection motivation. In Cacioppo BL, Petty RE (Eds.), *Social psychophysiology: a sourcebook*, London: The Guilford Press, 153–176.
68. Kasperson RE, Renn O, Slovic P (1988) The social amplification of risk: a conceptual framework. *Risk Anal* 8: 177–187.
69. Babcicky P, Seebauer S (2017) The two faces of social capital in private flood mitigation: opposing effects on risk perception, self-efficacy and coping capacity. *J Risk Res* 20: 1017–1037.
70. Entorf H, Jensen A (2020) Willingness-to-pay for hazard safety—A case study on the valuation of flood risk reduction in Germany. *Saf Sci* 128: 104657.
71. Kellens W, Zaalberg R, Neutens T, et al. (2011) An analysis of the public perception of flood risk on the Belgian coast. *Risk Anal* 31: 1055–1068.
72. Farabollini P, Lugeri FR, Lugeri N (2018) Humankind and Risk: a difficult history. In Antronico L, Marincioni F (Eds.), *Natural Hazards and Disaster Risk Reduction Policies*, 88–103.