Needed: A systems approach to improve flood risk mitigation through private precautionary measures

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Abstract

Private precautionary measures play an increasingly important role in flood risk management. The degree to which private precautionary measures mitigate flood risk depends mainly on the type of measure (and how effective it is) and how frequently and successfully it is implemented. These aspects are influenced by a complex interaction of physical and socio-economic processes, which makes the assessment and the prediction of the mitigation of flood risk via private precautionary measures a challenge. This paper provides an overview of factors and processes that influence the implementation and effectiveness of private precaution in mitigating flood risk, underpinning it with highlights from international examples. We recommend private precautionary measures for

further use to improve flood risk mitigation, but stress that they need to be considered and implemented through a holistic systems approach to maximize their effectiveness.

Keywords: private precautionary measures, systems approach, flood risk management

1. Introduction

In recent decades, there has been an increasing awareness of the need to shift flood risk management towards more integrated and adaptive strategies (Bubeck et al. 2016; Kreibich et al. 2015). One aspect of integrated flood risk management is the fact that it takes into account that flood defenses might fail and thus it is important to complement flood protection with non-structural solutions (Kreibich et al. 2015; Kunreuther et al. 2009). Therefore, there has been an increasing recognition of the need to shift the focus of flood risk management from flood protection, e.g. through structural measures, to reducing the consequences of flooding, e.g. through reducing vulnerability of communities (Klijn et al. 2015; Merz et al. 2010; Bubeck et al. 2012; Owusu et al. 2015; Hegger et al. 2016; Defra 2016).

In order to reduce societies' vulnerability to flooding, there has been an increasing focus on private precautionary measures as a viable method for flood risk mitigation. Private precautionary measures are those measures undertaken at the property level to mitigate flood loss to contents and building structures, for example the use of water barriers (Thieken et al., 2016). There are different types of private precautionary measures. They may reduce flood loss by, for example, preventing water from entering the property; by making structural changes to the building; through avoiding expensive fittings on the lower levels, or may take the form of planning which actions to take in case of a flood event, such as moving valuables to a higher floor (Kreibich et al. 2005). Private precautionary measures commonly implemented in Germany, for example, include "flood adapted use", "flood adapted interior fitting", "adapted building structure" and "flood barriers" (Kreibich et al. 2005). In other literature, private precautionary measures may be called "property level resilience measures" (Defra 2016), "property level flood risk adaptation" (Joseph et al. 2015),

51 "property-level flood protection" (Owusu et al. 2015), "repairable measures", "flood resilience",
52 "wetproofing" (Defra 2017a) or "resistance measures" (Defra 2008). In essence, they all describe
53 similar types of measures, so for consistency the term "private precautionary measures" or "private
54 precaution" will be used throughout the paper. In some cases, flood insurance is considered as a
55 private precautionary measure (e.g. Bubeck et al. 2013). However, while other private
56 precautionary measures have the aim to reduce loss, insurance only transfers the risk. Therefore,
57 in this paper, flood insurance is not considered as a private precautionary measure, but instead as
58 a factor that may influence the implementation of precautionary measures.
59
60 Studies have shown that private precaution can reduce loss (Kreibich et al. 2011; Hudson et al.
61 2014; Poussin et al. 2015; Sairam et al. 2019), but implementation/uptake levels are often low and
62 usually only rise following a flood event (Kreibich et al. 2010; Everett & Lamond 2013; Joseph et
63 al. 2015; Owusu et al. 2015). Knowledge about private precautionary measures and how to
64 incorporate them into a flood risk management plan is scarce (Kreibich et al. 2015). Recent
65 literature has provided more insight into public behavior in terms of private precautionary
66 measures (see Everett and Lamond (2013) and Hanger et al. (2018) for an overview) but a
67 comprehensive synthesis of how private precaution works within the flood risk system is lacking.
68
69 The aim of this paper is to provide a scientific overview of internal and external factors and
70 processes within the flood risk system that influence the implementation and effectiveness of
71 private precaution in mitigating flood risk. This overview is underpinned with some highlights
72 from international examples based on qualitative and quantitative research. We recommend private
73 precautionary measures for further use to improve flood risk mitigation but stress that they need

to be considered and implemented through a systems-approach to maximize their effectiveness. Implementing a systems approach requires considering all the processes and interactions of the flood risk system. Hence, one should consider flood risk reduction strategies through a comprehensive assessment of the effects and effectiveness of all types of measures together (e.g. structural measures, emergency measures, precautionary measures) instead of considering each measure on an individual basis. Interactions and feedbacks between these measures and the rest of the system may cause the overall effectiveness of these strategies to be different than the effectiveness of individual strategies on their own.

The remainder of this paper is structured as follows: we first discuss the complexity of the flood risk system and the need for considering the system as a whole, then we discuss private precaution from a governance perspective and finally we discuss the uptake and effectiveness of private precautionary measures. We conclude with a set of recommendations for a systems approach to improving flood risk mitigation through precautionary measures.

2. Complexity of the Flood risk systems

There has been an increasing awareness of the necessity to shift the focus of flood risk management from managing the hazard to also include the management of exposure and vulnerability. However, research that investigates and quantifies the impact of various factors (e.g. land use change, flood insurance, private precaution) and their interactions on flood risk is still scarce. Figure 1 shows flood risk with its three components and examples of the individual factors that may influence this risk. The diagram reflects the importance of considering flood risk management through private precaution from a systems perspective. The different components of flood risk, i.e.

hazard, exposure and vulnerability, are influenced by factors that are both internal and external to the flood risk system. Hazard, for example, is influenced by climate change (external factor) and by flood risk management measures such as structural protection (internal factor). External factors such as culture may influence flood risk exposure or vulnerability, but can also influence the flood risk governance approach. The different components of the flood risk system and their interactions are discussed in this and the next section along with the three examples shown in Figure 1 (example a and b in this section and example c in the next section). The factors and examples shown in the diagram and discussed in this paper are not exhaustive, nevertheless, they serve as examples to illustrate the importance of taking a systems perspective.

To detect the impact of the different factors on flood risk change, approaches that are based on empirical loss data have been implemented in the past, such as loss normalization studies (IPCC 2012; Bouwer 2011; Neumayer and Barthel 2011; Visser et al. 2014) or data-based approaches (e.g. Bubeck et al. 2012; Kreibich et al. 2005). Although these approaches have provided a better understanding of changes in flood risk, it is hard to determine the influence of the individual factors on risk change. Normalization studies, for example, show that trends in losses (i.e. risk) are not influenced by the effect of human-induced climate change (e.g. Barredo 2009). However, the effect of climate change may be undetected because it is likely to be mitigated by adaptation measures, such as improved early warning systems, strengthened flood protection, or better private precaution (Di Baldassarre et al. 2015; Handmer et al. 2012; Jongman et al. 2015; Mechler and Bouwer 2015; Metin et al. 2018). Simulation-based approaches have the advantage of being able to estimate the contributions of different drivers through scenario runs. However, many of the simulation-based studies only consider changes in hazard and exposure. Changes in vulnerability, e.g. because of private precaution, are often neglected (Metin et al. 2018). This is mainly due to a

lack of data and knowledge about changes in vulnerability and the effects on flood risk (Mechler and Bouwer 2015; Kreibich et al. 2019).

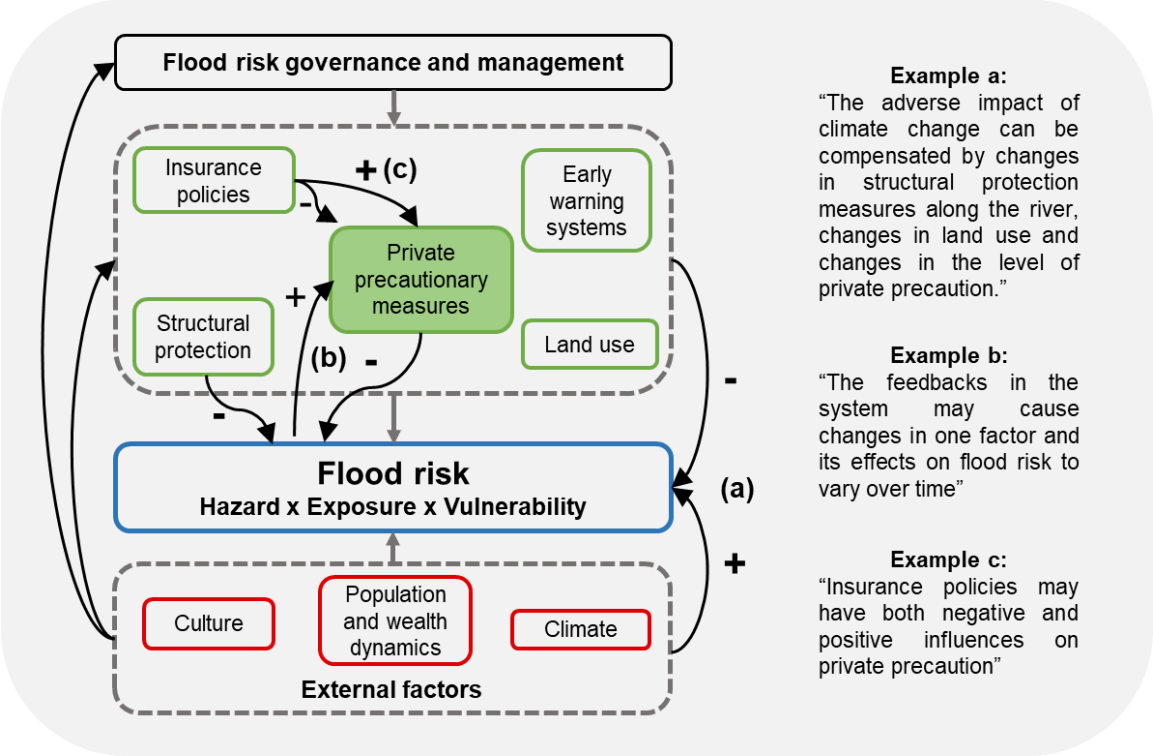
Metin et al. (2018) used a system-of-systems model (a model-system that couples detailed individual models that describe different processes, e.g. atmospheric, catchment and river processes or damage mechanisms), to quantify the sensitivity of flood risk to changes in the different risk systems, considering all components of the systems. They find that in the Mulde catchment in Germany, at the catchment scale, flood risk is most sensitive to changes in structural flood protection. The second largest contribution to flood risk comes from changes in land use, asset values and vulnerability (i.e. private precaution). The study also shows that the adverse impacts of climate change can be compensated by changes in structural protection measures along the river, changes in land use and changes in the level of private precaution. Example (a) in Figure 1 illustrates how the impact of different factors on flood risk should be considered simultaneously, since the impact of one factor may be masked or influenced by another factor.

When comparing the feasibility of the different measures (i.e. dike heightening, land use change and private precaution), the best strategy to compensate the effects of climate change, would be to increase the uptake of private precaution (Metin et al. 2018). These findings are specific to the example of the Mulde catchment and in another setting, private precaution may not be able to compensate for increases in risk that are caused by other factors (e.g. climate change). The study by Metin et al. (2018) shows that private precaution can be effective in decreasing flood risk and that for a comprehensive assessment it is important to simultaneously consider all the factors that are defining flood risk.

While the study by Metin et al. (2018) does take into account private precaution and its effects on flood risk, the authors do not consider changes in the different factors over time. Barendrecht et al. (2019) use a conceptual model to show that in Dresden preparedness (i.e. the uptake of private precautionary measures) has varied temporally and therefore its influence on loss or flood risk changes as well. These changes over time are the result of feedbacks in the system: due to a natural period without floods, people's awareness reduces (i.e. they forget about the risk) and therefore the uptake of private precautionary measures is low. This caused the flood related loss in 2002 to be higher than it could have been if more measures were implemented. In 2013, when awareness and the uptake of precautionary measures had increased due to the experience of the 2002 event, loss was much lower, even though the event was similar in magnitude to the event in 2002. This can also occur due to a "non-natural" period without flooding, which occurs when structural protection measures are implemented. On the contrary, if people are used to regular flooding, an adaptation effect may occur and they may be better prepared to deal with it (Barendrecht et al. 2019). Example (b) in Figure 1 illustrates the importance of considering feedbacks between the different factors of the system. It shows that changes in one of the factors that influences risk (e.g. the construction of structural protection) with the intention to reduce risk can have negative consequences and influences other factors, which may eventually increase flood risk. Changes in structural protection may also influence the uptake of private precaution in a more direct way. In a study on the implementation of private precautionary measures in the Italian Alps, Scolobig et al. (2012) find that trust in structural protection may be a reason for individuals not to increase their preparedness, even though they are aware of the risk. Bradford et al. (2012) found that respondents in Ireland were not aware of the flood risk despite having experienced flooding before. This lack of awareness was caused by the fact that respondents were living next to structural

protection that was constructed after they experienced flooding. The implementation of new structural flood defenses can also influence the existing adaptation and ability to mitigate flood risk of a society. Hazarika et al. (2016) contend that the people in the Upper Brahmaputra plain had adapted to the local flood situation by, for example, raising their houses and adapting agricultural practices. However, when the government implemented new flood control measures, which did not completely stop flooding from occurring but rather changed the nature of the flooding, the people were less able to cope with this new type of flooding, because their agricultural practices were not adapted to it.

These examples show that it is important to consider private precaution from a systems perspective (e.g. considering all the processes and interactions of the flood risk system) when studying its effects on flood risk as well aswhen considering the implementation of risk reduction measures. Intended or unintended consequences of actions need to be identified within the system in order to fully appreciate whether any flood risk management intervention will have a positive effect on reducing flood risk.



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183 **Figure 1.** The flood risk system with some of its factors and examples of the importance of
184 considering flood risk management through private precaution from a systems perspective. The
185 factors and links shown in this diagram are not exhaustive, they reflect the discussion in the text
186 and serve as examples to illustrate the importance of a systems perspective.

3. Flood risk governance and private precaution

Although there is a general tendency to move towards diversification in flood risk management, countries are struggling with implementation (Hegger et. al. 2016). The uptake of precautionary measures remains low, in part, because governments are dealing with challenges that hinder the implementation of private precautionary measures. For example, consideration of private precaution needs to occur at different phases of flood risk management (e.g. preparedness, response and recovery). Responsibilities also lie across different sectors (e.g. construction industry, planning, insurance, flood risk), government levels (national, regional, local) or with individual homeowners. Precautionary measures can be self-initiated by homeowners and/or directed or incentivized by government initiatives which adds additional governance complexity around implementation, including roles and responsibilities and any associated liabilities (Defra, 2017b).

In England, individuals are increasingly encouraged to take personal responsibility for managing their own flood risk (Johnson and Priest 2008). Correspondingly, in Germany, the German Federal Water Resource Act states that every person who is at risk of flooding has the obligation to take appropriate action (Rolfsen 2009) thereby initiating private precaution. A key challenge, however, is that households and businesses may still feel that it is the responsibility of the authorities to manage flood risk, usually in the form of structural measures (e.g. Owusu et al. 2015) thereby inhibiting their interest in self-protection. In Canada, Henstra et al. (2019) found that 55% of the public feels that homeowners are responsible for flood risk mitigation but the amount that respondents would be willing to pay for private precautionary measures would not be enough to reduce flood risk. This highlights another problem that arises with the shift of responsibilities

towards the individual: the question of who should fund private measures and arguments of elitism (e.g. only the richest being able to afford measures) if the burden falls solely upon individual homeowners (Penning-Rowsell and Priest 2015). Furthermore, technical implementation issues for private precautionary measures arise when there are interdependences between properties. In order to be effective some precautionary measures will need to be implemented (and operated) for multiple properties (Defra, 2017a). Joint-decision-making, financing and co-implementation in these situations can make the adoption of private precautionary measures considerably more challenging.

To encourage the implementation of private precautionary measures, governments may provide funding directly to affected households through post-event recovery grants (e.g. English Property Level Flood Resilience Grant Scheme, DCLG/Defra 2016; Joseph et al. 2015). In England, the government also proactively (ex-ante) funds private precautionary measures to manage property flood risk in particular situations, such as when it is not viable to implement structural measures(Mason 2014). In Germany and many other countries, such initiatives are absent and individuals are expected to privately fund their own precautionary measures (Rolfsen 2009; Surminski and Thieken 2017). Where government funding initiatives do exist these can help households overcome some of the financial barriers, although these initiatives still can have poor uptake (Suykens et al. 2016). The decision and motivation of households to invest in private precaution depends on multiple factors (as will be discussed in more detail in section 4). Households, for instance, may be constrained by their knowledge of the range and effectiveness of different measures, which can be enhanced if there are local flood groups or demonstration houses, like the Cumbria Resilience Showcase (Defra 2017b).

The availability of incentives such as reduced insurance premiums or continued availability of insurance could also influence individuals' interest in personally financed uptake, as shown by Poussin et al. (2014) for France. However, the lack of knowledge on the effectiveness of private precautionary measures hinders insurers' interest in funding them (Hudson et al. 2016). The insurance sector in the United Kingdom is working towards a 'flood performance certificate' that can be attached to a household to act as an incentive for reduced premiums (Surminski and Eldridge 2017). On the other hand, insurance may also negatively influence the uptake of precautionary measures, when households realise they will be compensated, thus reducing uptake motivation (Johnson and Priest 2008; Hanger et al. 2018). Thus, insurance policies can influence private precaution both positively and negatively which demonstrates the need for a systems approach. Example (c) in Figure 1 highlights the importance of considering the implementation of flood insurance schemes from a systems perspective, because of the unintended consequences it may have on private precaution.

Another governance challenge is the associated liability when private precautionary measures do not function as expected, as well as concerns about standards and product warranty. The availability and quality of precautionary measures is driven entirely by the private market and thus product design, construction quality and standards of implementation may vary. This challenge was highlighted by a local flood authority representative in England:

"It's a bit of a nasty beast because there are lots of commercial organisations. We've had enquiries from people that got the grant and then the stuff has failed and

then there is nothing they can do about it so then they come to us thinking that we go back to the original problem." (Local Authority interviewee, England)

Some guidelines and quality standards exist, for example the Flood Resilient Building Guidance for Queensland Homes (State of Queensland, 2019). However, there is a lack of consistency across the market and concerns about the selling of inappropriate and ineffective products (Defra 2017a; Defra 2017b) for associated flood hazard types (see also section 4). In an attempt to control this, in the United Kingdom, for example, a "Code of Practice and guidance for property flood resilience" is being developed and a new British Standard for flood products will replace an older one (Defra 2017b). However, the degree to which these are followed by developers, contractors and suppliers is unclear.

Private precautionary measures can act as a valuable addition alongside other flood risk management measures to reduce the residual risk and therefore reduce losses for extreme events. The identified governance challenges highlight the complexity of effectively implementing private precautionary measures. As the examples show, the actions of multiple actors (product suppliers, insurers, homeowners and governments) are interlinked and influence the uptake and effectiveness of precautionary measures. This warrants the need for a systems approach which recognizes the complex governance challenges of implementation.

4. Private precaution: motivation for uptake and effectiveness

The effect of private precaution on flood risk depends on the uptake of measures, i.e. whether people are motivated to adopt measures and whether they actually implement them, as well as on the effectiveness of the measures in mitigating loss. In this section, we discuss the factors of the

flood risk system influencing the willingness to take measures (motivation for uptake)and the loss-reducing effectiveness of private precautionary measures. Figure 2 focuses on these two aspects of private precaution and the factors influencing them.

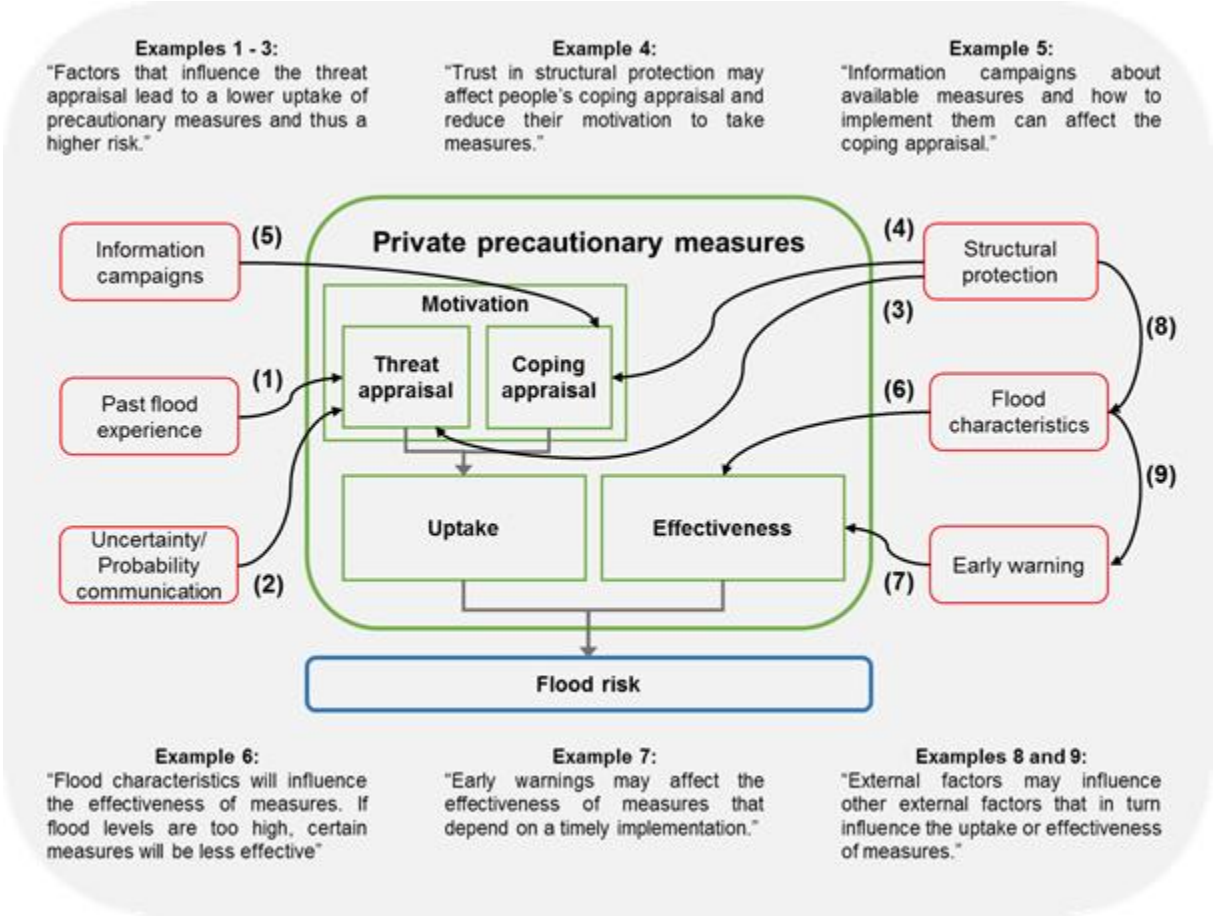

Figure 2. The aspects of private precaution and flood risk management factors influencing them.

The motivation for the uptake of private precautionary measures

According to protection motivation theory there are two important aspects that influence the motivation for the uptake of precautionary measures by private properties: threat appraisal and

coping appraisal (Bubeck et al. 2012) (see also Figure 2). Threat appraisal relates to the awareness of being at risk and to whether a threat is perceived. This is influenced by factors such as: flood experience, personal characteristics, and risk communication. Several studies observe that the experience of flood loss is positively correlated with the uptake of precautionary measures (Bubeck et al. 2013; Osberghaus 2015; Kreibich and Thieken 2009; Owusu et al. 2015; Poussin et al. 2014; Bradford et al. 2012; Wachinger et al. 2013). However, even though the experience of a flood may increase the awareness of being at risk, this can be undermined by authorities' actions or poor communication of the uncertainties and probabilities (Bell and Tobin 2007; Ludy and Kondolf 2012). An example of this occurred in Cumbria, where after the flood event in 2009 threat appraisal became very low. The authorities were speaking of an exceptional event that would not happen very often, therefore the residents and businesses felt safe behind the existing flood protection that they were told had a design period of 1 in 100 years and were surprised to be flooded again as soon as 2015 (Zürich 2015). A business owner that was affected by the floods in 2009 and 2015, indicated they were surprised that a second flood occurred again so soon:

> *"We were totally sure that it would never happen again. they said it was a one in a hundred year flood or something. And they built defences, so we were pretty confident that it wouldn't happen again. We had thoughts in mind of what we would do, but we didn't, we honestly didn't expect it to flood again, so rather naive I guess."* (Business owner, England)

Examples (1), (2) and (3) in Figure 2, illustrate that while factors like experience may have a positive influence on threat appraisal and thus on the uptake of measures, this positive influence may be canceled in combination with other factors like a poor communication about flood probabilities and the implementation of structural measures.

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312 The second factor, coping appraisal is a measure of how well people are able to cope with a threat.
313 It depends on the perceived self-efficacy, response efficacy and response costs (Bubeck et al.
314 2012). There may be different ways of coping with a threatening situation that do not all result in
315 an increase in the uptake of precautionary measures or adaptation (Bubeck et al. 2013). This can
316 include factors such as worry (Miceli et al. 2008; Raaijmakers et al. 2008) or trust in structural
317 protection (Scolobig et al. 2012; Wachinger et al. 2013). For example, Hanger et al. (2018) found
318 that respondents in Austria and England that are protected by public structural measures are less
319 likely to take private precautionary measures. Example (4) in Figure 2 highlights the influence of
320 other flood risk management measures like the construction of structural protection may have an
321 unintended effect on coping appraisal. Another reason for people not to implement measures is
322 anxiety that this may influence future house prices, because it identifies the property as being at
323 risk of flooding (Burningham et al. 2008).

324

325 Coping appraisal also depends on whether people have the knowledge and resources to implement
326 measures. Several studies have shown that it is important to include information about the specific
327 measures themselves and their benefits as a part of risk communication in order to increase the
328 uptake of measures (Grothmann and Reusswig 2006; Bubeck et al. 2013). In Appleby (England),
329 for example, people were willing to implement measures, but did not know which measures to
330 implement. A pilot project that provided funding for surveys and measures helped people to choose
331 the correct measures and increased the uptake of private precaution (Harries 2009). A study in
332 Canada highlights the importance of considering the difference between the general intention to
333 implement private precautionary measures and the willingness to implement individual measures

(Seebauer and Babcicky, 2020). The former is more influenced by fear and risk perception, while the latter instead depends more on the perceived response efficacy and costs (Seebauer and Babcicky, 2020). Example (5) in Figure 2 highlights the importance of providing adequate information about measures and how to implement them to increase people's coping appraisal.

The effectiveness of private precautionary measures

The effect of private precautionary measures in reducing flood losses to building structures was found to be non-marginal. In Germany, the loss prevented by implementing private precautionary measures was estimated to be between €11,000 and €15,000 per household, per event (Sairam et al. 2019). This accounts for 27% of the average incurred damages to household buildings in Germany during the flood events between 2002 and 2013.. Hudson et al. (2014) estimated that individual measures such as flood adapted use or flood adapted interior fitting reduce damages to household building structures in Germany by €14,385 and €11,302 and damage to household contents by €6,732 and €5,202, respectively. Research in the United Kingdom has shown that measures can reduce damages by 50 – 100% (Thurston et al. 2008). In France, Poussin et al. (2015) find that precautionary measures may reduce building and contents damages by up to €6,500. The most effective measure was elevating the ground floor, which costs €25,000-69,000 to implement for existing buildings and €1900-9800 for new buildings (Poussin et al. 2015).

Poussin et al. (2015) also found that the effectiveness of the different measures depends on the characteristics of the flooding (i.e. slow onset river flooding, or rapid flash/coastal flooding), as well as on the closeness of the building to the source of the flooding. Also, the frequency of flooding strongly influences the cost-efficiency of private precautionary measures. Therefore, it is

357 important to identify appropriate measures for each type of building and flood risk. In Carlisle, for
358 example, flood gates would not have contributed much to reducing the loss of the 2015 event,
359 because water levels were too high (Cumbria County Council 2017). In this case other measures
360 might have been more appropriate, such as using a coating for walls, or replacing wooden with
361 brick or concrete floors. Example (6) in Figure 2 shows the importance of choosing the appropriate
362 measures for the location of interest, because the effectiveness of the measures depends on location
363 specific characteristics of both floods and buildings.
364
365 Cumiskey et al. (2017) categorized measures into active (requiring implementation just
366 before/during the event: e.g. flood barriers) and passive measures (which do not require
367 implementation: e.g. sealing the basement). The effectiveness of private precaution in reducing
368 flood loss depends on the quality of installation and timely uptake (for active measures) of the
369 appropriate measure. This shows again, that it is important to consider the effectiveness from a
370 systems perspective, since it may interact with or be influenced by other factors. For example, the
371 presence of early warning systems and whether they function properly, will affect the effectiveness
372 of active measures, since the implementation of those measures depends on residents being aware
373 of an approaching flood in a timely manner (Cumiskey et al. 2017). Example (7) in Figure 2
374 illustrated how the implementation of other flood risk management measures like early warning
375 systems may affect the effectiveness of private precautionary measures that require people to take
376 actions at the onset of a flood event.
377 Since the frequency of flooding has been shown to determine whether private precaution is cost-
378 efficient (Poussin et al. 2015), this means that other flood management measures that reduce the
379 frequency of flooding, such as building structural protection, would reduce the cost-efficiency of

private precautionary measures. Climate change may also cause flood characteristics to change, which may influence the technical effectiveness of private precautionary measures, since it depends on flooding type and characteristics. The effectiveness of early warning also depends on flooding type and characteristics. Slow onset flooding happens slowly and usually gives people time to prepare, in the case of flash floods however, there is usually not enough time to provide a timely warning. Examples (8) and (9) in Figure 2 highlight how the different factors that influence the effectiveness of private precaution may also affect each other. Structural protection may change flood characteristics, which not only directly changes the effectiveness of measures but may in turn also affect early warning systems.

5. Conclusion

We argue that private precautionary measures can help to mitigate flood risk and should not be underestimated as part of a flood risk management strategy, especially with climate change putting increasing pressure on existing risk management strategies. However, private precaution can only be effectively implemented if it is considered from a holistic systems perspective. The strength of the role of precautionary measures depends on many interrelated aspects within the risk management system which may reduce or strengthen its effectiveness. Up to now, both research and flood risk management have been focusing mostly on individual aspects.

We propose several strategies for adopting a systems approach, concerning the aspects of flood risk data, modelling and governance. It is crucial to increase our understanding of the systems and interactions using a comprehensive documentation of past events encompassing hydrological aspects, structural protection failures, early warning, private precautionary measures implemented

as well as losses that occurred. In addition to these event-specific data, information on changes in several aspects of flood risk management that occurred between different flood events can improve the understanding of the system as a whole as well as the effect of different components. This information is especially valuable to understand the impact of variations in government policies and behavior of individuals and communities influencing the implementation and effectiveness of planned and implemented measures.

A number of modelling approaches may be implemented in combination with findings from empirical data to understand the drivers of flood risk, their interactions and feedbacks, and to quantify the influence of their combined effect on the entire system. The modelling approach that is adopted, depends on the assumptions, the level of complexity and the system components. This includes, but is not limited to, conceptual models or system-of-systems models. These models potentially combine all or at least multiple aspects of the flood risk system, their interactions and feedbacks. Though many of these models are theoretical, it is very important that they depict the reality of the system and are useful for practitioners. Therefore, we strongly recommend rigorous evaluation of these models using empirical data.

Implementing private precaution effectively requires collective action across multiple actors, including the public and private sectors, insurance companies and product suppliers, local and national governments, individuals and homeowners. Further research is needed to understand the governance challenges and the most appropriate governance mechanisms (e.g. legal regulations, partnerships, funding schemes) to enable stronger coordination across these actors and encourage uptake of private precaution. Furthermore, a better understanding is needed on the role of private precaution within the landscape of other flood risk management measures, and how the balance

between different measures could evolve over time, as more extreme and frequent flood events are expected.

While this review focuses on the use of private precautionary measures as part of a flood risk management strategy, the recommendation to use a systems approach applies to the risk management of any natural hazard, not only floods. Similarly to managing flood risk, private precautionary measures also play an important role in the risk management of wildfires, hurricanes or earthquakes and their effectiveness and implementation is influenced by many factors (Martin et al. 2007, Verrucci et al. 2016, Hudson et al. 2017). In the future, an even more holistic systems approach may include considering multi-hazard risk.

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