Exploring public and private flood adaptation with an empirically grounded socio-hydrological model

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Abstract:

Systems-dynamics based models can convert a narrative on human-flood interactions into a time-series that illustrates the possible evolution of interacting social and hydrological flood processes. However, there is a great need to improve such process-based human-flood models by grounding them on relationships revealed by empirical data. In this work, a model is developed based on a large data set of 3700 household surveys on flood risk perceptions and management from various locations in Austria. The focus of the model is on the expected coupled-interactions between household flood damages, public measures at the community level that reduce exposure to flooding, and private measures at the household level that reduce vulnerability to floods. Model outputs show how the experience of flood damages drives the implementation of private household flood management measures. These measures lead to a reduction in vulnerability that is particularly valuable in the time period directly after a flood has been experienced and before public measures that reduce exposure have been implemented. While this suggests that adaptation to flooding is reactive, the model also shows that by increasing regular support available to householders to enable them to implement private measures by a factor of ten (relative to the status quo), the damages in the event of a 100 year flood could be almost 50% lower than they would be without such support. Taking a proactive approach to implementing large scale public measures by increasing resources for these by a factor of 10 would achieve a more rapid and extensive reduction in exposure that would substantially reduce future damages from the 100 year flood. The benefit of a proactive approach to implementing public measures, rather than continuing in a reactive manner is particularly apparent when modelling how large floods might occur sooner than could be expected without climate change and preparation in advance will minimise future losses. However, because such investments might be unrealistic due to financial, technical or social limitations, modelling shows how support for private household measures could reduce future damages substantially, but the relatively rapid decay rate in household measures would need to be addressed through adequate support for operation and maintenance. These findings point to the potential value of support for private household measures in the time period before public measures are implemented and/or in settings where they are infeasible.

Keywords: Public-private interactions, household preparedness, flood exposure, flood vulnerability, Austria, integrated flood risk management, socio-hydrology,

1 Introduction

Floods place huge stress on our societies. Estimates suggest that 23% of the worlds' population is directly exposed to 1-in-100-year floods (that have a 1% chance of occurring in any given year), meaning that over the course of an average lifespan residents of such locations are more likely than not to experience a major flood (Rentschler et al., 2022). The impacts of "being flooded" on individual health and wellbeing, including mental health are substantial (Alderman et al., 2012; Fothergill et al., 2021). In many areas, the impacts are expected to increase as settlements grow and expand into flood risk zones (Retschler et al., 2023), and more frequent or changed seasonality of floods (Blöschl et al., 2017; 2019) put additional pressure on the existing systems that have evolved for mitigating and living with floods (Kam et al., 2021).

Established flood management strategies range from those at individual households, such as raising the property to ensure it stays above the water line, to larger community endeavours such as embankments, levees and river walls that hold back water and reduce flood exposure. In many regions, engineering advances and investments have led to the implementation of extensive, publicly funded, structural protection measures. Yet often there are neither the means nor the resources to eliminate the largest of floods through structural measures, meaning that for many householders' floods have never been experienced, but could happen. Hydrological work shows that megafloods, though rare, are well within the realms of possibility (Bertola et al., 2023). Global warming may generate higher magnitude rainfall events than previously experienced, further raising the likelihood of flooding (Bloeschl et al., 2019). Furthermore, structural flood mitigation measures are often exceeding their operational lifetimes, or are suffering from under investment in their long-term maintenance. As such, the likelihood of events that surpass the capacity of large defence infrastructure could be expected to rise (Dotteri et al., 2018; Kreibich et al., 2022; Schlogl et al., 2021).

Integrated flood risk management recognises these risks, and focusses on reducing both flood exposure and flood vulnerability through a suite of public and private measures (Nordbeck et al., 2019; Rauter et al., 2020). While exposure describes whether water inundates the property and is reduced through public measures, vulnerability relates the severity of the flood impacts to the capacity of the affected individuals to anticipate, cope and recover from floods (Kuhlicke et al., 2011). Lower vulnerability is based on the individual's or household's availability of financial capital (e.g. money), human capital (e.g. education) as well as wider economic and political processes beyond the individual that impact the individual, such as social capital (e.g. knowledge exchange and trust between individuals), social norms, structures and practices (e.g. whether household flood protection is normal and most household have it) (Kuhlicke et al., 2020). Households with more capital have the capacity to implement private household management measures such as insurance to cover flood damage, emergency planning, and flood proofing, that reduce their flood vulnerability (Few, 2003; Kreibich et al., 2015; Saiman et al., 2019).

Much empirical and theoretical research has explored the mechanisms driving the uptake of private household measures (Bamberg et al., 2017). Protection-motivation theory, an established framework from psychological risk research, helps understand why households might or might not adopt private household flood management measures. It considers individual actions as emerging as a response to a combination of threat appraisal (i.e. ones fear of being flooded) and coping appraisal (i.e. ones perceived ability to cope with the flood, which includes capacity to take an action that could meaningfully reduce the impacts) (Kuhlicke et al., 2020). Therefore, based on these interconnections, public measures that reduce exposure to flooding and provide householders with a sense of protection against flooding, could also diminish threat appraisal and subsequently lead to a decrease in private household protection, and an increase in vulnerability. Bamberg et al.'s (2017) meta-analysis found just such a pathway, though between threat appraisal and intent to implement measures. While the evidence is in no way definite, it suggests that the interactions between public measures, threat appraisal, flood events, and household measures are worthy of attention that will enable their interconnections to be accounted for in flood risk management planning.

Furthermore, recent work has argued that unintended outcomes, such as an increase in vulnerability due to public measures, should be more carefully considered by hydrologists and water managers (Sivapalan and Bloeschl, 2015). The levee effect is one such phenomenon. This effect arises when large infrastructure is constructed for flood defences that subsequently keeps flood prone land dry and enables it to be developed. This can lead to an area with a dense population, a high value and a high vulnerability. Modelling suggests, that if, or when, a large flood occurs and defences fail, more catastrophic flood losses could result than if flood defences would not have been built (Barendrecht et al., 2017; Ciullo et al., 2017; Di Baldassarre et al., 2013; Haer et al. 2020; Tonn and Guikema, 2018; Viglione et al., 2014).

There is therefore a critical need to better grasp the longer term interactions between flood events, public measures that reduce exposure and private measures that reduce vulnerability. This is not only to generate insights into how households and communities might fare in the event of a large but unlikely flood, but to explore how future damages might be minimised though optimised public and private efforts before a large flood event. Dynamic models, that can simulate flood risk change through time, in response to both extreme events and changes in societal conditions, would enable the long-term trajectories of the existing system to be analysed and improvements, or optimisation strategies to be explored. Several models have been developed to specifically explore how flood damages could change through time as a result of public and private actions. The agent based model developed by Haer et al., (2020) shows how proactive governance that implements public measures before flooding is experienced leads to lower total damages than reactive governance that implements measures after a flood. While Tonn and Guikema, (2018) model the change in flood damages in a small community based on individual responses to both perceived flood risk and coping appraisal. Their agent-based model shows how a shift to community measures leads to a reduction in household measures, and while this generally reduces total damages, a large flood that exceeds mitigation measures means significant damages occur. The work presented here builds of these studies, but focuses on examining how responsibility sharing between public actors and private households could reduce household flood damages in different flood risk zones.

2 Socio-hydrological modelling

The concept of socio-hydrology was proposed by Sivapalan et al (2012) in response to the clear relevance, but under-inclusion of human actions in shaping hydrological systems. The premise of socio-hydrology is that human behaviour drives changes in hydrology (for example through actions that modify the path and flow rate of water) and that humans respond to the resulting changes in hydrology (for example, by utilising land from which water flow has been diverted). The interactions between the modified hydrological system and human actions and responses drives a co-evolutionary process, leading to emergent, and sometimes unexpected, behaviour (Sivapalan and Bloeschl 2015), such as increased flood risk (Di Baldassarre et al., 2013).

Several studies have attempted to analyse, understand, and in some cases predict, the dynamics between humans and floods using either an agent-based or system-dynamics based approach. While agent-based models simulate how the behaviours of many different individuals (i.e. agents) lead to a collective system outcome (see Zhuo et al., 2020), system-dynamics based models explore broad stylised relationships. Both approaches have strengths and weaknesses, but one advantage of the systems-dynamics approach is the simplicity and transparency of the modelling that that is focussed on developing knowledge through the modelling process rather than the model outcomes (Forrester, 1985). As such, the method is very well suited for structuring the examination of complex interconnected relationships between natural and social processes for which there remains great uncertainty (Hayden, 2019). However, the field of socio-hydrology remains very much in its infancy. Dynamic modelling of natural-social process interactions is often challenged in identifying and observing the interconnections empirically, and especially, determining the rates at which they are changing through time (Barendrecht et al., 2019).

Furthermore, most socio-hydrological models take a hydro-centric approach, whereby flooding is often the “master variable” (Hall, 2018) and the experience of flooding is often conceptualised as driving change in society (e.g. Di Baldassarre et al., 2013 and extensive subsequent work based on this model). For example, Barendrecht et al. (2021) model how flood events drive awareness that drives preparedness that reduces subsequent flood damages. While flood experiences are the driving variable, they recognise that flood experience is one of many factors that could impact flood preparedness (see Kuhlicke et al., 2020). For example, research highlights that humans choose their actions based on perceptions and preferences that are influenced by a range of factors, including socio-economic-political contexts, that extend well beyond the hydrological situation (Wesselink et al., 2017; Zeitoun et al., 2016). There is a need to engage in this fundamental debate about socio-hydrological model structure (see Kreuger and Alba, 2022; Thaler, 2021) and the extent to which it is accurate to conceptualise human-flood systems as co-evolving and self-reinforcing through empirically based model development.

In this research, first the interactions between flood risk and the implementation of public and private measures are conceptualised (based on theory) and identified (based on data). Secondly, a socio-hydrological, systems dynamics based model is developed and parameters are estimated to describe the rates of change in the observed interrelationships. Thirdly, the model is used to explore the implications (in terms of flood exposure, vulnerability and damages) of social and hydrological changes.

3 Case study, data and methods

Context of the case study: Austria, an alpine country in central Europe, experiences localised and regional flooding fairly frequently. Flood risk management has a long history (Fuchs et al., 2017), and is currently realised through a range of institutional agencies operating at different governance levels (Rauter et al., 2020). Public authorities are primarily considered to be responsible for flood risk management, which leads to a prioritisation of community level protection and often results in structural risk management measures. This is noted to have led to a "lock in", whereby land use is largely unrestricted and "perverse subsidies" can promote property development in flood risk areas, further generating a greater need for flood protection (Fuchs et al., 2017; Seebauer et al., 2023). A shift in responsibility for flood risk management from the public sector, towards private householders, is expected to achieve a risk based management approach, but existing governance structures are noted to do little to encourage property level flood risk adaptation measures (Rauter et al., 2017). Yet, despite the limited institutional support, research shows that householders do, to varying extents, implement property level flood protection and preparedness measures (Seebauer and Babcicky, 2020; Babcicky and Seebauer, 2017).

Household data: The data set used in this study consist of 3770 household responses from flood prone municipalities in Austria, taken during four different survey campaigns between 2014 and 2020. Details of the surveys are provided in Seebauer and Babcicky (2020; 2021); Babcicky and Seebauer (2019; 2020) and Babcicky et al. (2021). The surveys conformed with ethics guidelines of the involved research institutions and the pooled data set was anonymised. For this study, the survey responses relating to multiple questions on each of the themes of perceived threat of flooding, degree of damage experienced, degree of reliance on public flood protection measures, perceived effort to implement household measures, as well as intent to implement measures were pooled together to item indices. See Supporting Material 1 for list of survey question responses that were pooled together for each theme. Z-scores were calculated to normalise the indices within each survey campaign, thus allowing to pool data from different survey regions and survey years. Surveyed households also stated whether a flood had been experienced, when a flood was last experienced, how many times a flood has been experienced, whether the householder believed they lived in a flood risk zone, as well as the presence and number of household preparedness and structural measures implemented. Household preparedness relates to measures such as an insurance policy that covers flood damage and an emergency preparedness plan, while household structural measures include installing flood barriers at doors and windows and placing electrical system above the water line (see Supporting Material 1).

Methods: Firstly a conceptual model was developed based on prior work and existing understanding to describe the expected drivers and interactions between public and private flood measures (Fig. 1). Secondly, the pooled survey data was analysed in R, to test and refine the expected relationships empirically. Estimates of the probability density function (Kernel Density Estimates) were calculated by pooling the data into groups by whole-number Z-score intervals. Statistical significance was determined with the Kruskal-Wallis test. Thirdly, a systems dynamics based model consisting of linked non-linear differential equations was produced. Parameters were identified based on the literature as well as conversions from vector autoregression models developed from a longitudinal data set from the case study region (Seebauer and Babcicky, 2021) to ordinary differential equations (see Supporting Material 2). Finally, after parameter calibration, model scenarios were generated to explore system behaviour.

4 Modelling interactions between public and private flood management measures

4.1 A conceptual model of private-public flood management interactions

The conceptualisation of the interactions between public and private flood management and resulting flood damages (Fig. 1) is based on the classic model of risk being equal to hazard multiplied by exposure multiplied by vulnerability (Barendrecht et al., 2017). Exposure is controlled by public measures that prevent households being inundated, and vulnerability is controlled by household preparedness (e.g. implementing a flood action plan, moving valuable possessions to higher levels) and structural measures (e.g. water tight doors and windows, values to prevent backflow on drains etc.). In the event of a flood (that exceeds the public protection measures), the household measures will reduce the damages. Public measures that reduce exposure, are conceptualised as emerging through path dependency, in that past responses and established institutional arrangements drive their ongoing implementation and maintenance (Hanger-Kopp et al., 2022; Seebauer et al., 2023). Public measures are also continually being advanced to reduce exposure through technological and institutional innovation and financial resources (Kreibich et al., 2022; Seebauer et al., 2023). Advancements and innovations include classic engineering structures as well as innovations in flood zone mapping and flood hazard prediction coupled with measures such as mobile defences, and policy and planning developments that reduce settlement in a flood zone. Household measures are expected to be driven by residents appraisal of flood threat combined with their ability to take action (coping appraisal) (Grothhmann and Patt, 2006). Both the experience of flooding and recognition that potential damages could occur is expected to change the uptake and implementation of public and household measures (Fig. 1). While external factors such as flood risk information, individual capacity and social vulnerability change the threat and coping appraisal (Kuhlicke et al., 2020).

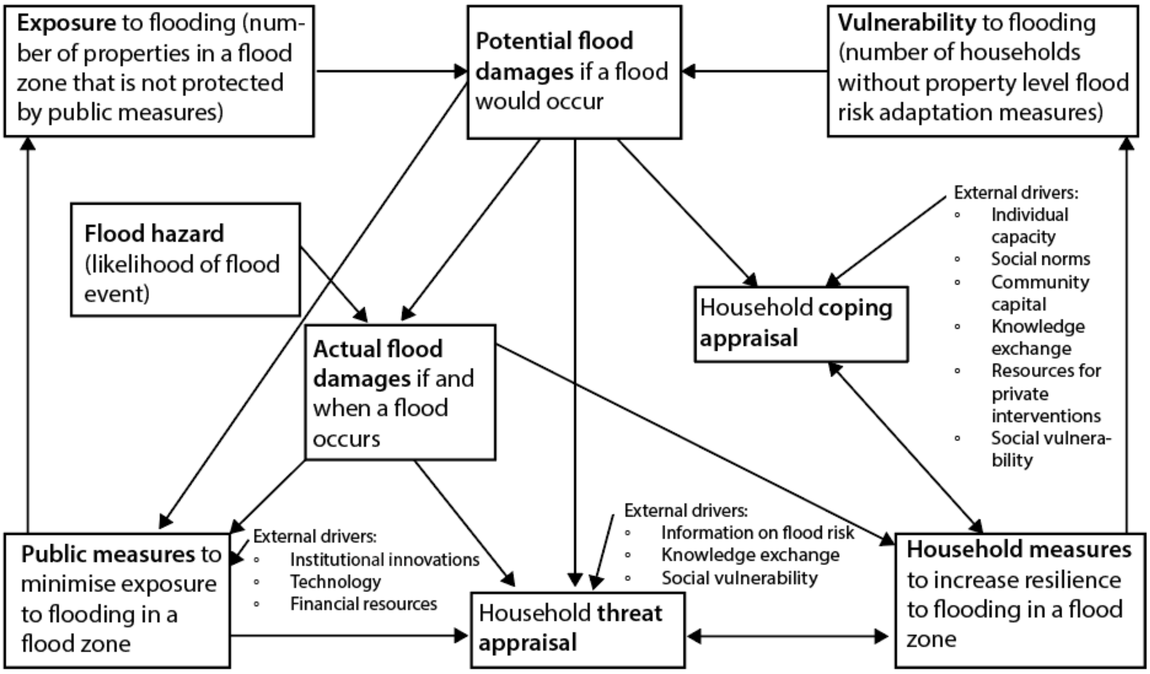


Figure 1. Conceptual model for public–private flood management interactions

4.2 Identifying household empirical relationships to derive a descriptive static model

The conceptual model is converted into a descriptive, static model by examining the relationships in the data (Fig. 2).

Flood experience, flood damages, public measures and threat The data show that the experience of flooding correlates to an increase in perceived threat (Fig. 2a). There is a significant difference between the mean of the Z-score for perceived threat of flooding between households that have experienced flooding (mean Z-score for threat = 0.435, n= 1019) and those that have not experienced flooding (mean Z-score for threat = -0.173, n=2688). Furthermore, households that have higher (self-reported) flood damages report higher perceived threat of flooding. Fig. 2b shows a general tendency of the higher the damages, the more concentrated the perceived threat is around larger values i.e. an increase in damages correlates with an increase in threat. It can be presumed that the experience of damages drives the increase in perception of flood threat, rather than an increase in perceived threat drives an increase in reported damages.

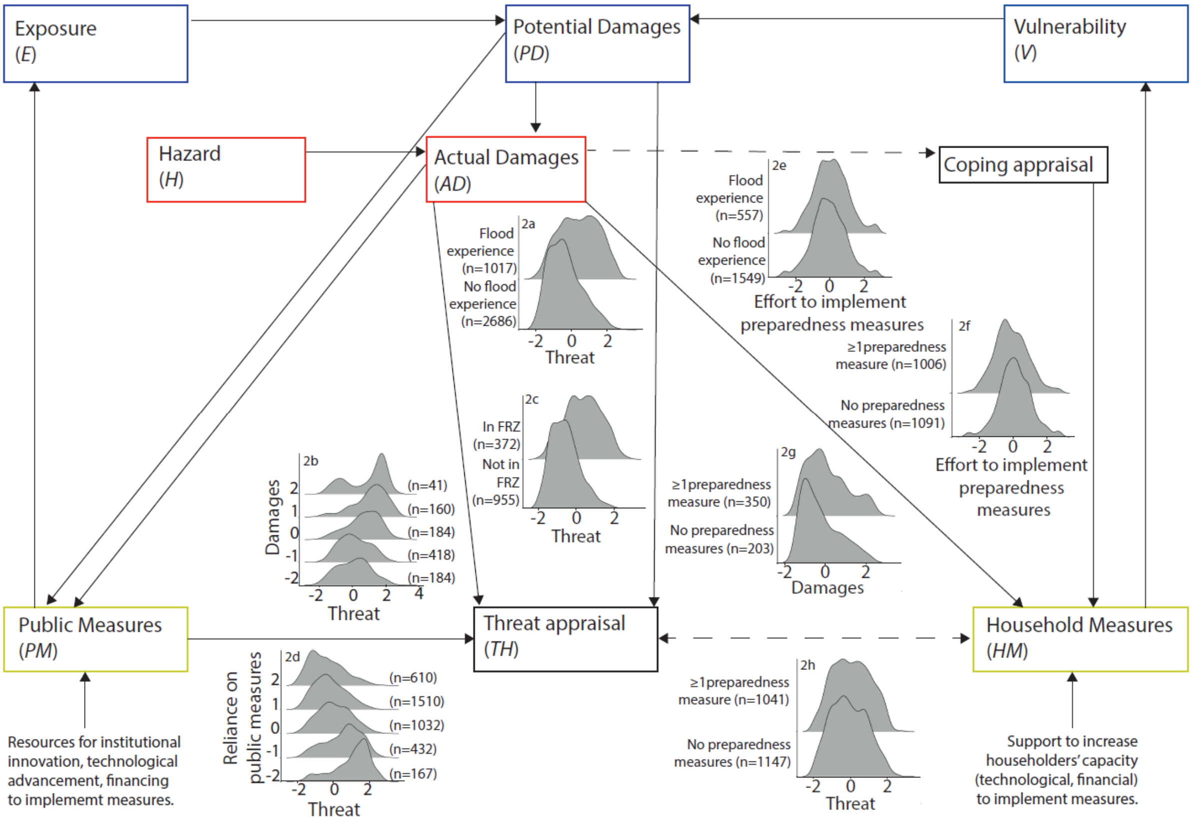


Figure 2. Conceptual model and graphs of probability density functions for Z-Scores from the pooled household survey data (grouped by whole-number Z-score intervals). (2a) perceived threat of flooding according to whether the householder has prior experience of flooding; (2b) perceived threat correlated to damages; (2c) perceived threat, for householders who have never experienced a flood, according to whether the householder identifies as living in a flood risk zone (FRZ) or not; (2d) perceived threat correlated to reliance on public measures for protection against flooding; (2e) perceived effort to implement household preparedness measures, according to whether the householder has prior experience of flooding; (2f) perceived effort to implement household preparedness measures, according to whether the householder has already implemented one or more household preparedness measures; (2g) damages experienced, according to whether householder has one or more preparedness measures; (2h) perceived threat, according to whether householder has one or more preparedness measure.

Householders' awareness to the risk of potential flood damages also seems to increase their perceived threat of flooding (Fig. 2c). Householders who identify with living in a flood risk zone (even though their personal assessment may be incorrect) can be expected to have a higher awareness to potential flood damages. Analysis shows there is a strong and statistically significant difference between the mean Z-score for perceived threat for the households who have never experienced a flood, yet identify with living in a flood risk zone (mean Z-score for threat = 0.363, n= 372) and those who have never experienced a flood and identify as not living in a flood risk zone (mean Z-score for threat = -0.584, n= 957) (Fig. 2c).

Householders' perceived threat of flooding seems to be strongly influenced by the extent to which they rely on and trust in the public and municipality measures for flood protection. Fig. 2d shows how perceived threat is negatively correlated with reliance on public measures. The direction of this relationship is inferred as increased reliance on public measures leads to a reduced perception of threat, rather than increased perceived threat leads to a lower reliance on public measures. However, there is also no discernible relationship between reliance on public measures and implementation of household measures, suggesting that while reliance on public measures reduces perceived threat, it does not impact whether or not households implement measures.

Flood experience, flood damages and coping appraisal Using the survey data on the perceived effort to implement household measures as an indicator of the householders' appraisal of their ability to take meaningful actions to counter flood risks, there is a small and only slightly statistically significant difference between the effort to implement preparedness measures for the householders that have experienced a flood (mean Z-score for perceived effort=0.081, n=557) and those that have not experienced a flood (mean Z-score for perceived effort=0.026, n=1549) (p=0.047) (Fig. 2e). Note, that the mean Z-Score for effort is slightly higher in households that have experienced a flood. There is no difference detected for effort relating to structural measures and experience of flooding. This suggests that the aspect of coping appraisal related to effort for implementation does not respond strongly to personal experience of flooding, but if it does, householders' perception of the effort required for implementing measures could go up after experiencing a flood.

The data also suggest that awareness to flood risk has no clear impact on householders' coping appraisal as there is no difference in the perceived effort to implement measures between the households that identify or do not identify with living in a flood risk zone and have never experienced flooding. Overall, this analysis suggests that the aspect of coping appraisal related to the effort to implement measures, is driven by processes beyond flood risk perception and flood experiences.

Household measures, threat and coping appraisal It would be expected that households that do implement preparedness measures perceive the effort to implement them to be lower than those who do not implement them. The data confirm this with a highly statistically significant difference between the lower mean Z-score for effort to implement household measures for the households that have one or more household preparedness measures (mean Z-score for perceived effort = -0.108, n= 1006) and the higher score for the population that has zero preparedness measures (mean Z-score for perceived effort = 0.098, n= 1091) (Fig 2f). Household structural measures show the same relationship. It is however, important to note that the direction of this relationship is unclear. While householders who perceive the effort as lower may be more inclined to implement measures, it is also likely that householders who have already implemented measures perceive the effort to be lower.

There is a statistically significant difference between Z-scores for the degree of damages experienced for the households that have one or more household preparedness measure and those that have zero preparedness measures (p=0.0001) (Fig. 2g). A similar relationship is noted for household structural measures, but with much lower statistical significance (0.01). The direction of this relationship is logically inferred as being that an increase in damages drives an increase in household measures rather than an increase in household measures drives an increase in damages. However, household measures should reduce damages. The reasons why this is not shown by the data could be because householders are reporting on flood damages in the past, but household measures are reported in the present (at the time of the survey). The damages in the past may have motivated them to implement measures, but damage reduction benefits will only be noticed after the next (future) flood.

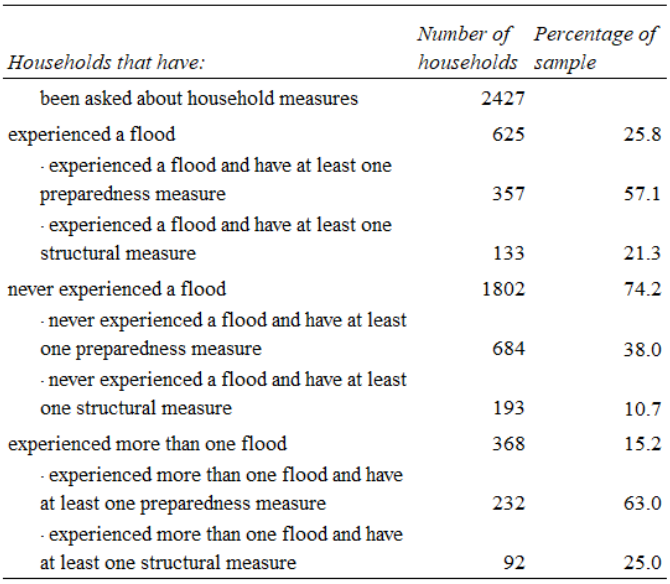
There is a small but statistically significant difference between the Z-score of perceived threat for the households that have one or more household preparedness measures and the households that have

0 preparedness measures (p=0.003) (Fig. 2h). However, the direction of this relationship is unknown. Threat could motivate householders to implement measures, but it could also be that households that have measures perceive the threat of flooding to be higher than those that do not have measures. There is no statistically significant difference between perceived threat in households that do and do not have structural measures. This strongly suggests, in line with other work that points to considerable inconsistency in the effects of risk perception (e.g. Bubeck et al., 2012; van Valkengoed & Steg, 2019), that it cannot be assumed that a perception of threat is a driving factor for the implementation of measures, nor that by implementing measures the perception of threat is alleviated.

Finally, 38% of households that have never experienced a flood report having preparedness measures (including insurance) and 11% report having structural measures (Table 1). This must be interpreted with caution, but it does suggest that while personal experience of damages are a major driver of household measures, other forces that raise coping appraisal, such as resources and support, play a very important role.

Refined model Based on the household data analysis, a refined model was constructed (Fig. 3). The link between flood damages and perceived effort to implement measures (an aspect of coping appraisal) was removed because of the low observed impact of flood experience and damages on coping appraisal. The link between threat appraisal and household measures was also removed, due to the unknown direction and very low observed impact of threat perception on the implementation of household measures. Threat perception therefore responds to changes in potential damages, actual damages and public measures, but it does not have an impact on household measures. If for a different setting, the data suggest that household measures do respond to threat, the link can be added to further drive up household measures.

Table 1. Number of households with private protection measures (preparedness and structural) according to whether they have or have not experienced flooding



Households that have:	*Number of households*	*Percentage of sample*
been asked about household measures	2427	
experienced a flood	625	25.8
- experienced a flood and have at least one preparedness measure	357	57.1
- experienced a flood and have at least one structural measure	133	21.3
never experienced a flood	1802	74.2
- never experienced a flood and have at least one preparedness measure	684	38.0
- never experienced a flood and have at least one structural measure	193	10.7
experienced more than one flood	368	15.2
- experienced more than one flood and have at least one preparedness measure	232	63.0
- experienced more than one flood and have at least one structural measure	92	25.0

4.3 Adding dynamics – developing a numerical model

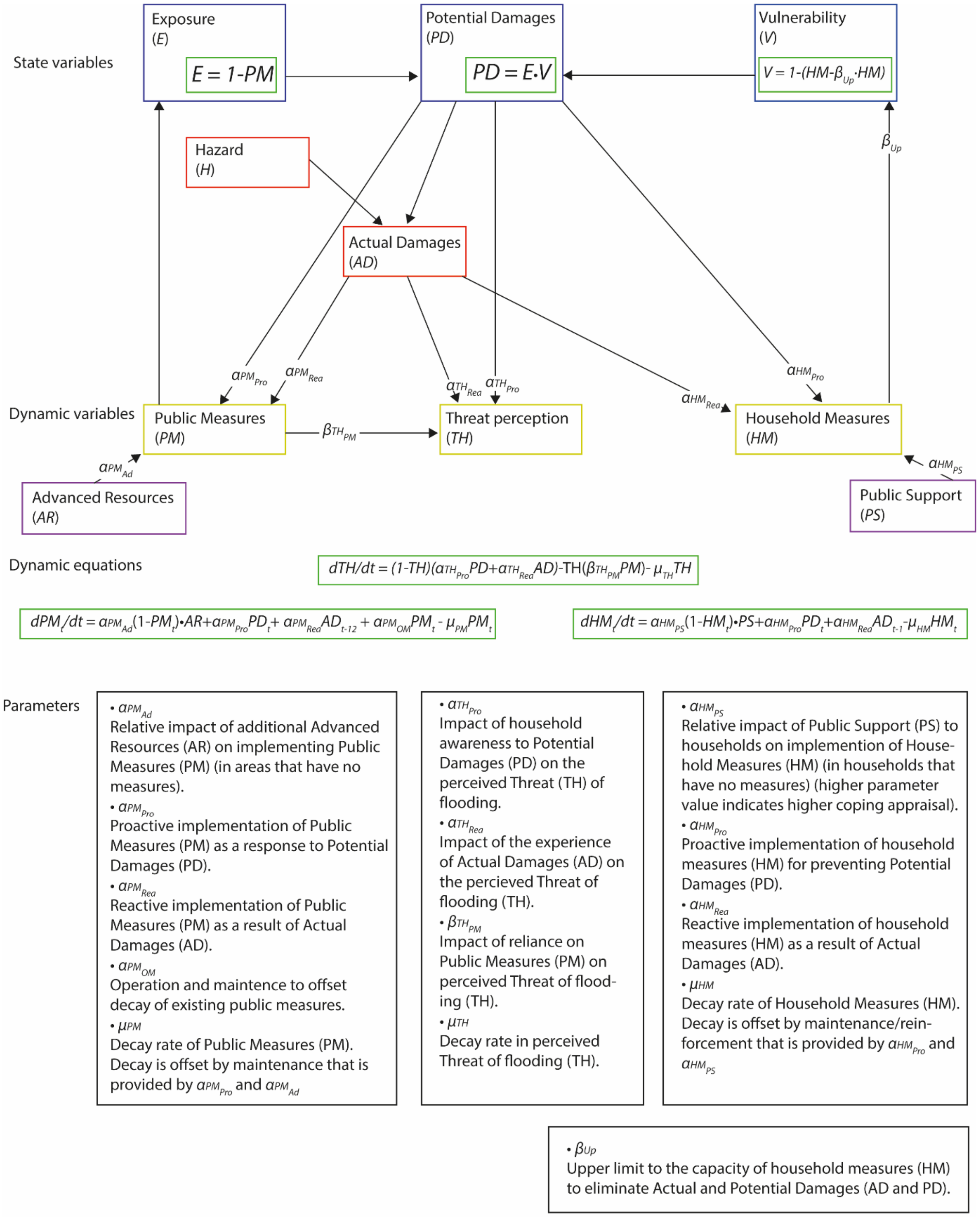
To take the model from static (whereby an understanding about the relationships between the variables has been determined, shown in Fig. 2) to dynamic, whereby the system changes over time, model equations are developed that adopt parameters to determine how fast the variables change through time (Fig. 3).

The model (shown in Fig. 3) is a continuous-time dynamical system in which all components take on values in [0,1], and depend on time (t), E = E(t)):

Hazard (*H*) of flooding is described as a Dirac comb:

$$H = X = \Delta_T(t) = \sum_{n \in \mathbb{N}} \delta(t - nT) \quad (1)$$

$\delta(.)$ refers to the Dirac delta function. $H(t) = 0$ except for multiples of T $(T, 2T, 3T, \ldots)$, at which points $H(t) = \infty$ with (local) integral equal to 1, which represents the occurrence of a flood event. While the assumption of pre-determined rather than randomly generated flood events is unrealistic, it is deemed appropriate to improve analytical simplification in this study because the timing of the floods themselves is not the object of interest. Instead the focus of the analysis is the implementation of flood protection in the presence and absence of floods and the corresponding impact on long-term flood damages.



Dynamic equations

$$dTH/dt = (1-TH)(\alpha TH_{Pro}PD+\alpha TH_{Rea}AD)-TH(\beta TH_{PM}PM)- \mu_{TH}TH$$

$$dPM_t/dt = \alpha PM_{Ad}(1-PM_t)\bullet AR+\alpha PM_{Pro}PD_t+ \alpha PM_{Rea}AD_{t-12} + \alpha PM_{OM}PM_t - \mu_{PM}PM_t$$

$$dHM_t/dt = \alpha HM_{PS}(1-HM_t)\bullet PS+\alpha HM_{Pro}PD_t+\alpha HM_{Rea}AD_{t-1}-\mu_{HM}HM_t$$

Parameters

- αPM_{Ad}
  Relative impact of additional Advanced Resources (AR) on implementing Public Measures (PM) (in areas that have no measures).
- αPM_{Pro}
  Proactive implementation of Public Measures (PM) as a response to Potential Damages (PD).
- αPM_{Rea}
  Reactive implementation of Public Measures (PM) as a result of Actual Damages (AD).
- αPM_{OM}
  Operation and maintence to offset decay of existing public measures.
- μPM
  Decay rate of Public Measures (PM). Decay is offset by maintenance that is provided by αPM_{Pro} and αPM_{Ad}

- αTH_{Pro}
  Impact of household awareness to Potential Damages (PD) on the perceived Threat (TH) of flooding.
- αTH_{Rea}
  Impact of the experience of Actual Damages (AD) on the percieved Threat of flooding (TH).
- βTH_{PM}
  Impact of reliance on Public Measures (PM) on perceived Threat of flooding (TH).
- μTH
  Decay rate in perceived Threat of flooding (TH).

- αHM_{PS}
  Relative impact of Public Support (PS) to households on implemention of Household Measures (HM) (in households that have no measures) (higher parameter value indicates higher coping appraisal).
- αHM_{Pro}
  Proactive implementation of household measures (HM) for preventing Potential Damages (PD).
- αHM_{Rea}
  Reactive implementation of household measures (HM) as a result of Actual Damages (AD).
- μHM
  Decay rate of Household Measures (HM). Decay is offset by maintenance/reinforcement that is provided by αHM_{Pro} and αHM_{PS}

- βUp
  Upper limit to the capacity of household measures (HM) to eliminate Actual and Potential Damages (AD and PD).

Figure 3. Model equations and description of the parameters

The model is designed to be spatially versatile, in that its variables are represented as values between 0 and 1 that can be “mapped” to the real world using data on the actual or estimated number of houses exposed to floods and the actual or estimated value of flood damages if these houses are inundated and they do or do not have household flood protection measures in place. The spatial unit for this modelling approach are the individual flood zones. This is the space that lies within either the 30, 100 or 300 year flood return period (Fig. 4). This area could be determined through combined hydrological and hydraulic flood zone mapping that takes into account existing flood protection measures (Blöschl et al., 2022).

Properties in the 30, 100 or 300 year flood zone are intermittently exposed to flooding but those that adopt private preparedness or structural protection measures have a reduced vulnerability. As new public measures are implemented to reduce the incidence of flooding in the 30, 100 or 300 year flood zones, the number of properties exposed to flooding will decrease. As more households adopt private preparedness or protection measures the vulnerability to flooding will decrease. Flood zones are modelled separately and the damages for each flood zone can be aggregated together to generate an estimate of damages in the area/region/community of interest.

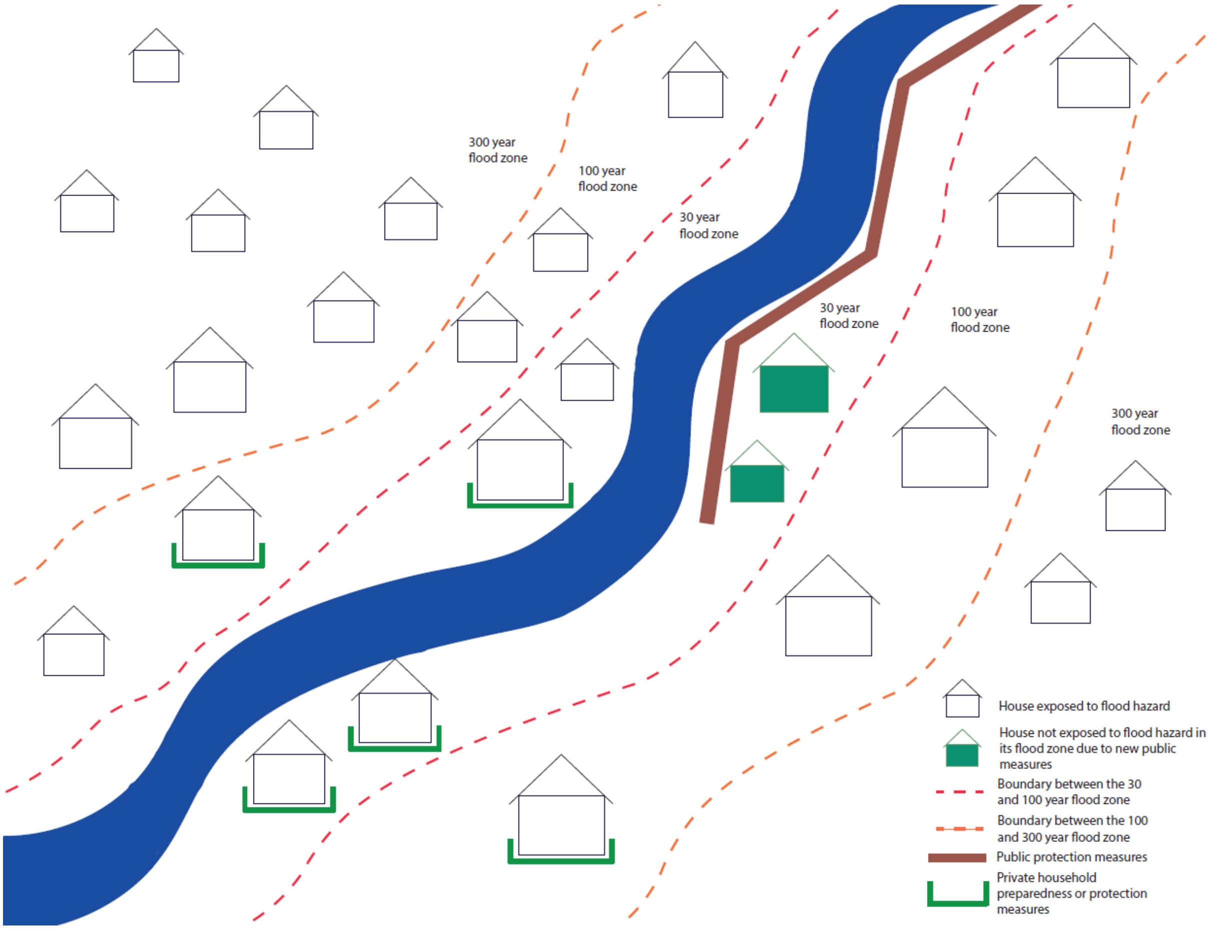


Figure 4 Schematic representation of properties located in the 30 and 100 year flood zones. The probability of flooding in each flood zone includes the effect of public protection measures to reduce the likelihood of flooding and therefore the exposure based on the conditions at time 0. Exposure within the flood zone therefore decreases as new public measures are implemented. Properties that have household preparedness or protection measures have a reduced vulnerability to flood damages.

4.3.1 The state variables

Exposure (E) describes the proportion of houses in the flood zone of analysis, that would be inundated if a flood would occur (on a scale of 0 – 1) (Eq. 2). Exposure decreases with increasing Public Measures [PM]. Therefore when Public Measures are 1, Exposure is 0 (e.g. no households will be inundated) and when Public Measures are 0, Exposure in the flood zone is 1 meaning that all households are fully exposed.

$$E = (1 - PM) \quad (2)$$

Vulnerability (V) describes the proportion of households in the flood zone who do not have Household Measures (HM) and will experience maximum damages if they are inundated (on a scale of 0 - 1). In this model, vulnerability is reduced through the uptake of household measures, therefore as HM increase, V decreases. The literature suggests a limit to the capacity of household measures to reduce vulnerability (Aerts et al., 2014; Crick et al., 2018; Du et al., 2017b, Dubbeldoer et al., 2017; Haer et al., 2019; JBA., 2013; Kreibich and Thieken, 2009; Kreibich et al., 2015; Sairam et al., 2019), so even if household measures were 1, V would not reach 0. This residual vulnerability is accounted for by placing an upper limit on HM (the parameter β_{Up}) (Eq 3).

$$V = 1 - \left(HM - \beta_{Up} \cdot HM\right) \quad (3)$$

Potential Damages (PD) are the damages or losses in the flood zone that would be measurable if a flood occurs. They are the result of exposure (E) multiplied by vulnerability (V) (Eq. 4a).

$$PD = E \cdot V \quad (4a)$$

Potential damages can also be calculated in monetary terdms (e.g. Euro) if the total number of houses in the flood zone of analysis is known or can be estimated, plus the average cost of flood damages per house (without household measures) is known (Eq. 4b).

$$PD_{€} = E \cdot Number\ of\ houses \cdot V \cdot Cost\ per\ house \quad (4b)$$

Actual Damages (*AD*) are the damages or losses that occur when a flood happens. They are the result of exposure multiplied by vulnerability and hazard (with hazard being either 0 whereby there is no flood, or 1 meaning that there is a flood) (Eq. 5a). If no flood occurs, actual damages are 0, if there is a flood, then actual damages are equal to the potential damages at that moment in time. As with Potential Damages, Actual Damages can also be calculated in monetary terms (Eq. 5b).

$$AD = PD \cdot H = E \cdot V \cdot H \quad (5a)$$

$$AD_{€} = E \cdot Number\ of\ houses \cdot V \cdot Cost\ per\ house \cdot H \quad (5b)$$

4.3.2 The dynamic variables

Public Measures (*PM*) determine the change in the proportion of the flood zone that is protected from flooding through public measures through time. The construction and maintenance of public measures results from concern about future flood damages (proactive actions), response to actual flood damages (reactive actions) and the availability or provision of Advanced Resources (AR) that enable public measures to be extended (e.g. digitalised and widely available flood risk maps, integrative institutions for flood risk management, additional financial resources, evolution of land use regulations that prevent new buildings on flood risk zones, and resettlement schemes to move people out of risk areas). The proactive parameter α_{PMPro} acts on the Potential Damages (PD) and would be higher in regions/communities that take a proactive planning approach to flood risk management (Eq. 6) (see Haer et al., 2020). The reactive parameter α_{PMRea} acts on the Actual Damages (AD) and would be higher in places where measures tend to be implemented after flood events. A delay in implementation (12 years) is placed on the reactive response to represent the time it takes after a flood has occurred to realise the implementation of public measures (10–13 years on average) (Seebauer et al., 2023). Advanced Resources (AR) are controlled by the parameter, $\alpha_{PM_{Ad}}$ that determines the relative impact of external resources on the implementation of new measures. Public measures require maintenance and operation to ensure they can achieve their utility when needed. This is represented by the parameter, $\alpha_{PM_{OM}}$, that acts on the existing public measures. If maintenance is insufficient, they decay through time, represented by the parameter μ_{PM}. This exponential decay parameter aims to capture the "point in time when the infrastructure is expected to have lost half of its purpose or utility" (Givoni and Perl, 2020, pp. 84).

$$\frac{dPM_t}{dt} = \alpha_{PM_{Ad}}(1 - PM_t) \cdot AR + \alpha_{PM_{Pro}}PD_t + \alpha_{PM_{Rea}}AD_{t-12} + \alpha_{PM_{OM}}PM_t \ - \mu_{PM}PM_t \quad (6)$$

Threat (TH) determines the change in the average household perceived threat of flooding through time. Threat is mainly accumulated through actual flood damages. The impact of damages on threat is modulated by the parameter $\alpha_{TH_{Rea}}$ (Eq. 7). Awareness to potential damages also play a significant role, which is determined by the parameter $\alpha_{TH_{Pro}}$. Public measures generate a sense of safety that lowers the perceived threat. The extent to which public measures reduce threat is determined by the parameter $\beta_{TH_{PM}}$. Threat also has a decay rate, represented by μ_{TH} that describes the average rate at which householders cease to be concerned about flooding, for example, because other issues dominate their concerns, or their memory of flooding and the fear it generates reduces. Similar to public measures, threat is also conceptualised as decaying exponentially.

$$\frac{dTH}{dt} = (1 - TH) \cdot \left(\alpha_{TH_{Pro}}PD + \alpha_{TH_{Rea}}AD\right) - TH\ (\beta_{TH_{PM}}PM) \ - \mu_{TH}TH \quad (7)$$

Household measures (HM) determines the change in the proportion of households in the flood zone of analysis that adopt any form of Household Measure to reduce their damages from flooding through time. Householders are motivated to implement measures when they experience actual damages, which is modulated by parameter $\alpha_{HM_{Rea}}$ (Eq. 7). A delay in implementation of 1 year is placed on the reactive response to represent the time it takes after a flood has occurred to realise the implementation of new measures. Potential damages as a driver for the implementation of household measures is modulated by parameter $\alpha_{HM_{Pro}}$. In some settings this may be relevant, but for this data set, no clear relationship was seen between awareness to potential damages (householders who identify as living in a flood risk zone) and the implementation of household measures. Rather, the external driver, Public Support (PS), modulated by $\alpha_{HM_{PS}}$ is conceptualised as being the major driver of household measures by supporting householders who do not have measures, or no longer have measures that they previously had, to (re)implement them. It represents individual financial and human capital and social norms that influence household capacity to implement private flood protection. Household measures also have an exponential decay rate, represented by μ_{HM} that describes the half-life of structural and preparedness measures, such as forgetting what to do in an emergency, degradation of sand-bags or window seals. In this study, household preparedness and structural measures are grouped together and considered simultaneously (see description in Table 2).

$$\frac{dHM_t}{dt} = \alpha_{HM_{PS}}(1 - HM_t)PS + \alpha_{HM_{Pro}}PD_t + \alpha_{HM_{Rea}}AD_{t-1} \ - \mu_{HM}HM_t$$

(7)

4.4 Model parameterisation and calibration

Parameter values to determine the speed at which variables change through time are estimated based on the literature, an 18 month longitudinal data set from Seebauer and Babcicky (2021), or calibrated to achieve model outcomes that fit the observed system behaviour (e.g. Carr et al., 2022, see Sivapalan and Bloeschl, 2015) (Table 2). To simplify the modelling process, a key assumption is made, that variables change steadily through time and parameters remain therefore constant. However, slightly different parameter values were given for the three different flood zones (30 year, 100 year, 300 year) because the processes taking place in each unit are expected to vary for a hypothetical Austrian municipality (Table 3). The model was programmed and run in Anylogic 8.8.6. The baseline (representing the status quo) scenario was generated by calibrating certain parameters (see Table 2) to produce model outputs that reflect the current situation flood management situation in a typical Austrian municipality.

Table 2 Parameters for the modelled scenarios for each flood zone (30, 100 and 300) and the grounds for their selection. Parameter descriptions provided in Fig. 3. All units are yr^{-1}.

Parameter	*Explanation and justification*
Public measures	
$\alpha_{PM_{Ad}}$	The relative impact of the ongoing development of advanced resources, that include flood risk maps and warning systems, new agencies and organisations that engage in flood risk management, and new financial resources specifically for developing innovative integrative approaches for flood risk management is calibrated at 0.01 yr^{-1} in the 30 year flood zone, 0.001 yr^{-1} in the 100 year flood zones and 0.0001 yr^{-1} in the 300 year flood zone. This achieves low but steady implementation of public measures in the *Baseline* scenario to reflect more support being provided to communities at greater flood risk. This reflects the Austrian situation at the national scale, whereby steady continual innovations (e.g. digitalisation of flood risk maps, mobile flood defences and advancements in flood forecasting) are driving a reduction in exposure (Kreibich et al., 2022). To model the impact of increasing advanced resources on flood adaptation in the *Increased Advanced Resources* scenario, this parameter is doubled to 0.02 yr^{-1} in the 30 year flood zone, and increased by a factor of 10 and 100 (to 0.01 yr^{-1}), in the 100 year flood and 300 flood zones respectively. To model the impact of *Limits to Public Measures* this parameter is reduced by a factor of 100 in each flood zone.
$\alpha_{PM_{Pro}}$	The impact of awareness to potential flood damages that drives proactive implementation of public measures is set considerably lower (ranging between 0.01 yr^{-1} in the 30 year flood zone and 0.0001 yr^{-1} in the 300 year flood zone) than the reactive parameter because in Austria, most public measures are expected to be implemented reactively rather than proactively.
$\alpha_{PM_{Rea}}$	Reactive implementation of public measures after flood experience is expected to be the dominant driver and this parameter is calibrated to obtain expected system behaviour and is consistently set at 0.9 yr^{-1}. To model the impact of *Limits to Public Measures* this parameter is reduced by a factor of 100 in each flood zone.
$\alpha_{PM_{OM}}$	Operation and maintenance to offset decay. This is set as equivalent to the public measure decay rate in the *Baseline* scenarios to capture that maintenance and operation resources are adequate to overcome decay, but lowered by a factor of 100 in the *Limits to Public Measures* scenarios to capture a scenario where resources for operation and maintenance are vastly inadequate, resulting in decay.
μ_{PM}	The annual operation and maintenance costs of dikes and floodwalls are reported to range from 0.01% to 1% of the total investment costs, while for retention ponds, the range is from 1-6% (Aerts, 2018). A consistent decay rate of 0.01 yr^{-1}, corresponding to a half-life of 50 years, is selected for this analysis.
Threat	
$\alpha_{TH_{Pro}}$	Householders who are aware they live in a flood risk zone, have a higher perceived threat of flooding (Fig. 2c). However, this parameter is set low (ranging between 0.01 yr^{-1} and 0.0001 yr^{-1}) because the majority of householders are not aware that they live in a flood risk zone. It is expected that householders residing further from the river have lower awareness to living in a flood risk zone therefore this parameter is set lower in the 100 and 300 year flood risk zones.
$\alpha_{TH_{Rea}}$	Personal experience of flooding raises the perceived threat (Fig. 2b). The parameter value is calibrated to obtain expected system behaviour whereby perceived threat rises as a response to flood damages resulting in a parameter value of 1.

$\beta_{TH_{PM}}$	Public measures reduce householders' perceived threat of flooding (Fig. 2d). Longitudinal data taken at an interval of 18 months (Seebauer and Babcicky, 2021) suggest that threat goes down by about 0.1 yr^{-1} as reliance on public measures increases. See Supporting Material 2.
μ_{TH}	Longitudinal data show that threat decays in the absence of flood damages (Seebauer and Babcicky, 2021). This is estimated at a rate of 0.13 yr^{-1}, corresponding to a half-life of just over 5 years. See Supporting Material 2.
Household measures	
$\alpha_{HM_{PS}}$	External support that raises a householders coping appraisal and drives the implementation of measures comes through both individual financial and human capital (education level, financial resources, time to spend on implementing measures, and accessibility to knowledge and information) (Johnson et al., 2023) and social norms on household flood protection measures. This parameter value is calibrated at 0.03 yr^{-1} in the *Baseline* scenario, to achieve household measure of 0.3 in the absence of flood experience (i.e. 30% of households have at least one preparedness or structural household measure) (Table 1). For the *Increase Public Support* scenario this is increased 10 fold to 0.3yr^{-1}.
$\alpha_{HM_{Pro}}$	No clear relationship was seen between awareness to potential damages (householders who identify as living in a flood risk zone) and the implementation of household measures and therefore in this work this parameter was consistently set at 0.
$\alpha_{HM_{Rea}}$	The reactive implementation of household measures is calibrated at 0.9 yr^{-1} in the *Baseline* scenario, to generate the rapid and substantial increase in household measures immediately following flood damages. In the *Increased Public Support for Household Measures* scenario this is lowered to 0.65 yr^{-1} to reflect the higher initial level of household measures when public support is greater and therefore the lower impact of flood experience on reactive implementation.
μ_{HM}	Longitudinal data taken at an interval of 18 months, with no flood in this time, suggest a very rapid decay rate for household emergency plans of 0.45 yr^{-1}, corresponding to a half-life of about 1.5 years (see Supporting Material 2). However, the decay rate for other preparedness measures, such as insurance is expected to be much slower. For household structural measures, a decay rate can be estimated from the reported annual operation and maintenance costs that range between 1-3% of the investment costs (Aerts, 2018). The upper limit of these estimates are used to estimate a decay rate for household structural measures of 0.04 yr^{-1}, corresponding to half-life of 17 years. A lumped decay rate of 0.07 yr^{-1} is used in the scenarios to capture both rapidly decaying preparedness measures such as emergency preparedness plans, and slowly decaying measures such as insurance and structural adaptations. This corresponds to a half-life of 10 years.
β_{Up}	An estimate of the maximum reduction in damages achieved through household measures if the property is inundated. Structural measures are expected to have a greater impact on damage reduction than preparedness measures. A reduction of 70% through a combination of preparedness or structural measures is used in the scenarios (based on data cited in Haer et al., 2019; Harries, 2012).

Table 3 Parameters for the modelled scenarios for each flood zone (30, 100 and 300) and the grounds for their selection. Parameter descriptions provided in Fig. 3. All units are yr^{-1}.

	Baseline			*Climate Change*			*Increase Advanced Resources for Public Measures*			*Increase Public Support for Household Measures by a factor of 10 in all flood zones*			*Limits to Public Measures (reduce Advanced Resources, reduce Reactive response to flooding and reduce Operation and Maintenance by a factor of 100).*			*Off-set Limits to Public Measures by Increase in Public Support for Household Measures*		
	30 year	*100 year*	*300 year*	*30 year → 15 year*	*100 year → 50 year*	*300 year →150 year*	*30 year*	*100 year*	*300 year*	*30 year*	*100 year*	*300 year*	*30 year*	*100 year*	*300 year*	*30 year*	*100 year*	*300 year*
Public measures																		
$\alpha_{PM_{Ad}}$	0.01	0.001	0.0001	0.01	0.001	0.0001	0.02	0.01	0.01	0.01	0.001	0.0001	0.0001	0.00001	0.000001	0.0001	0.00001	0.000001
$\alpha_{PM_{Pro}}$	0.01	0.001	0.0001	0.01	0.001	0.0001	0.01	0.001	0.0001	0.01	0.001	0.0001	0.001	0.001	0.0001	0.001	0.001	0.0001
$\alpha_{PM_{Rea}}$	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.009	0.009	0.009	0.009	0.009	0.009
$\alpha_{PM_{OM}}$	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
μ_{PM}	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Threat																		
$\alpha_{TH_{Pro}}$	0.01	0.001	0.0001	0.01	0.001	0.0001	0.01	0.001	0.0001	0.01	0.001	0.0001	0.01	0.001	0.001	0.01	0.001	0.001
$\alpha_{TH_{Rea}}$	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
$\beta_{TH_{PM}}$	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
μ_{TH}	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13
Household measures																		
$\alpha_{HM_{PS}}$	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.3	0.3	0.3	0.03	0.03	0.03	0.3	0.3	0.3
$\alpha_{HM_{Pro}}$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
$\alpha_{HM_{Rea}}$	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.65	0.65	0.65	0.9	0.9	0.9	0.65	0.65	0.65
μ_{HM}	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07
β_{Up}	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70

5. Model scenarios

Five different management scenarios are generated to explore i) a baseline scenario showing the status quo for a hypothetical Austrian settlement, ii) increasing advanced resources to drive innovation in public flood risk measures, iii) raising public support for household measures, that represents an increase in universal coping appraisal and capacity of the household to implement measures, , iv) limiting the capacity of a municipality to implement new public measures and maintain those in existence , e.g. due to financial, technical or political constraints v) off-setting the limits to public measures by increasing public support for household measures.

4.1 Baseline scenarios demonstrate the adaptation effect

The modelled outputs of the baseline scenarios for the 30, 100 and 300 year flood zones, that are representative of a hypothetical Austrian settlement, stimulate the implementation of public measures that achieve complete flood protection (PM = 1) after two flood events in the 30 year flood zone (Fig. 5). Most flood protection measures are implemented reactively after flooding (Seebauer et al., 2021) and to reflect this the reactive parameter is set at 0.9. However, there is also steady development and innovation in public measures that is reflected by the parameter for advanced support. This is set higher, at 0.01 in the 30 year flood zone and lower at 0.01, and 0.001 in the 100 and 300 year flood zones respectively to reflect the prioritisation of protection measures in locations where flooding is more likely. As such, the model shows that public measures in the 100 and 300 year flood zones develop more slowly leading to a higher proportion of zone experiencing damages in the first floods they experience (Fig. 6). This combination of large reactive responses aligns with observations from Austria where projects are often initiated after flood events to reduce future exposure. The slower development in innovation the drives public measures is less often reported but also visible through improvements in early warning systems and mobile flood defences. This suggests that by increasing resources for advancing innovation the dependence on reactive responses could be reduced.

The reactive response at the household also means that preparedness measures are implemented rapidly in all flood zones immediately after flooding. These reduce the vulnerability to subsequent flood events in the aftermath of a flood (Fig. 7). For the 100 year flood zone, the reduction in vulnerability due to the implementation of household measures could play an important role in minimising loss and damages should a flood occur in the period of time during which public measures are in progress but not yet implemented (Fig. 8). This could be considered an adaptation effect, whereby damages are observed to be lower in subsequent floods. In this simulation, based on an empirical data set, the capacity of household measures to reduce flood damages has a significant, but short lived, impact on reducing vulnerability and potential flood damages due to the relatively rapid decay rate of household measures.

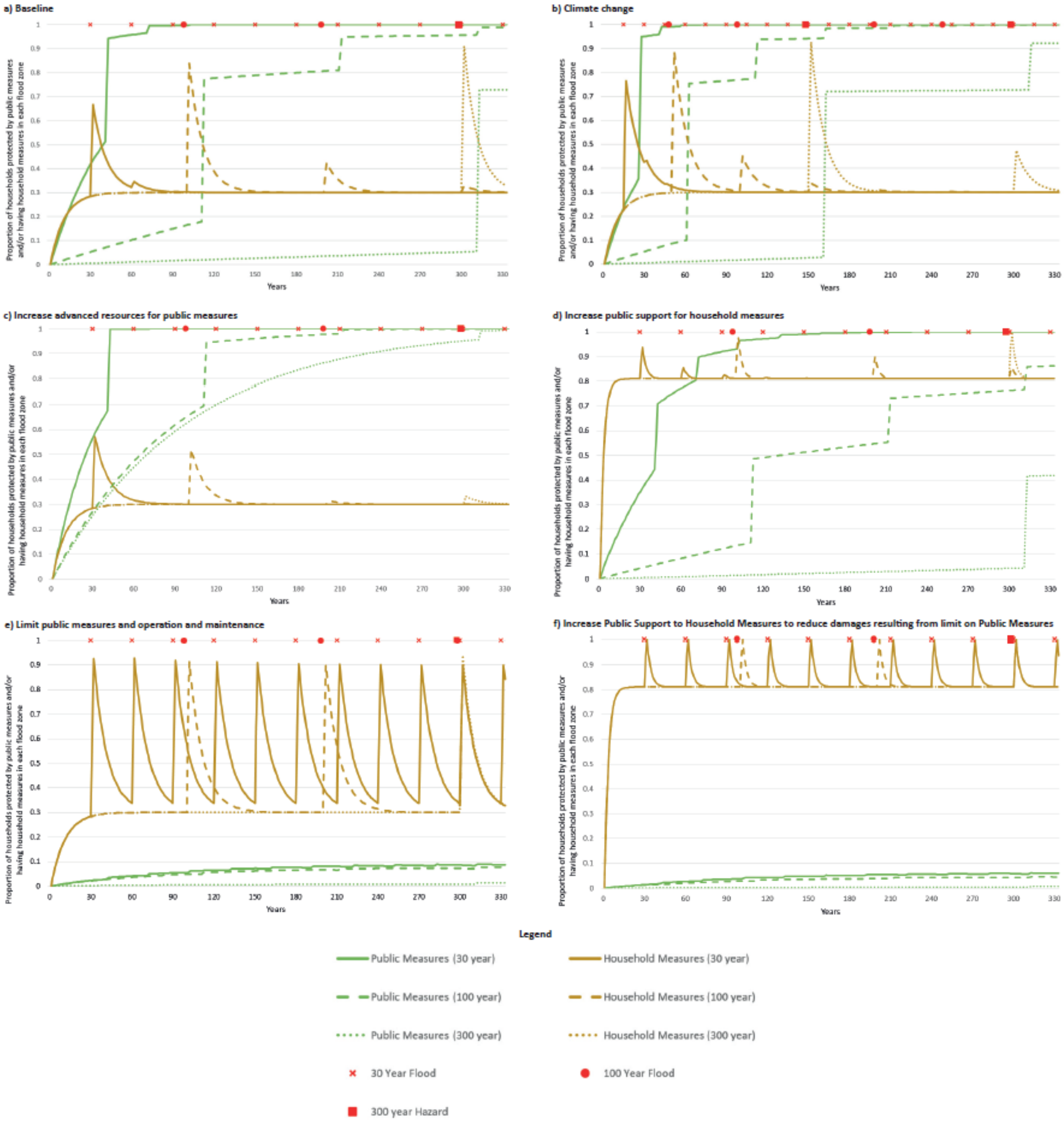


Figure 5 Proportion of households in the 30, 100 and 300 year flood risk zone protected by public measures and having household measures for each scenario a) baseline scenario; b) climate change scenario; c) increase in advanced resources for public measures scenario; d) increase in public support for household measures scenario; e) limit public measures at 0.6 and under investment in operation and maintenance; f) increase public support for household measures to off-set impacts of limits on public measures.

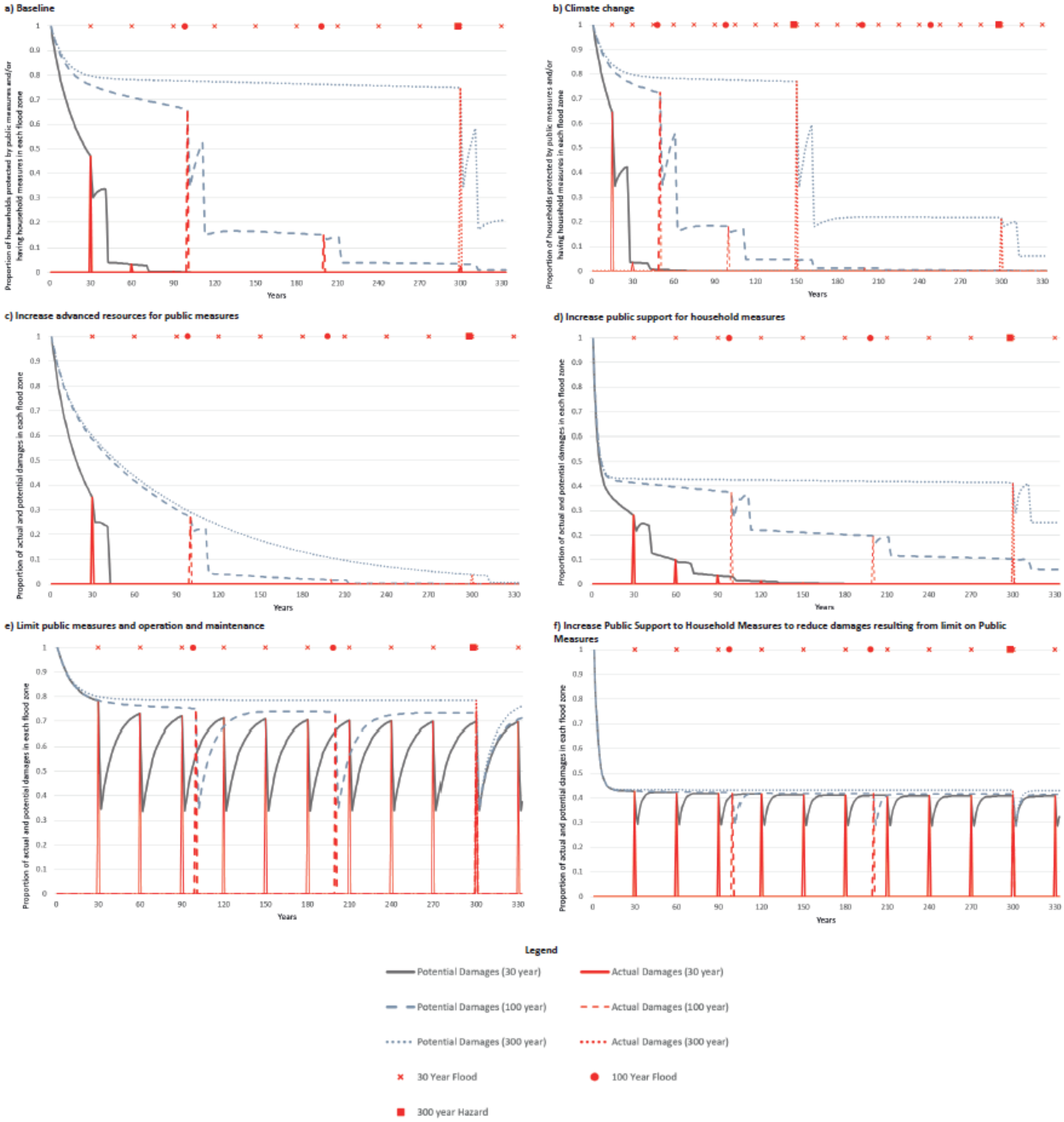


Figure 6 Proportion of total maximum damages that could occur to the households in the 30, 100 and 300 year flood zone for a) baseline scenario; b) climate change scenario; c) increase in advanced resources for public measures scenario; d) increase in public support for household measures scenario; e) limit on public measures of 0.6 and under investment in operation and maintenance; f) increase in public support for household measures to off-set impacts of limits on public measures.

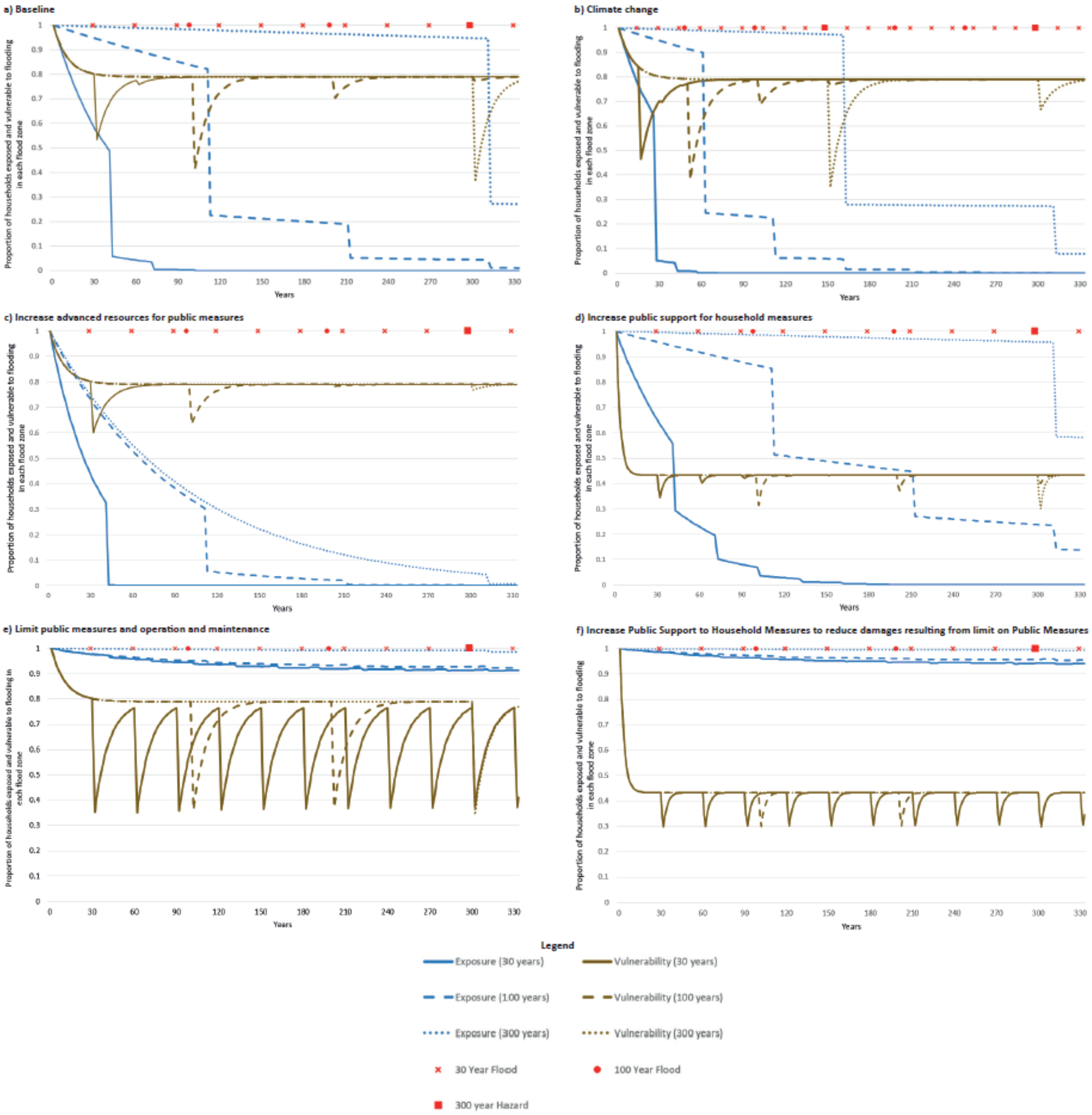


Figure 7 Proportion of households exposed (i.e. not protected by public measures) and vulnerable (i.e. not having at least one household preparedness or structural protection measure) to flooding in the 30, 100 and 300 year flood zones for a) baseline scenario; b) climate change scenario; c) increase in advanced resources for public measures scenario; d) increase in public support for household measures scenario; e) limit on public measures of 0.6 and under investment in operation and maintenance; f) increase in public support for household measures to off-set impacts of limits on public measures.

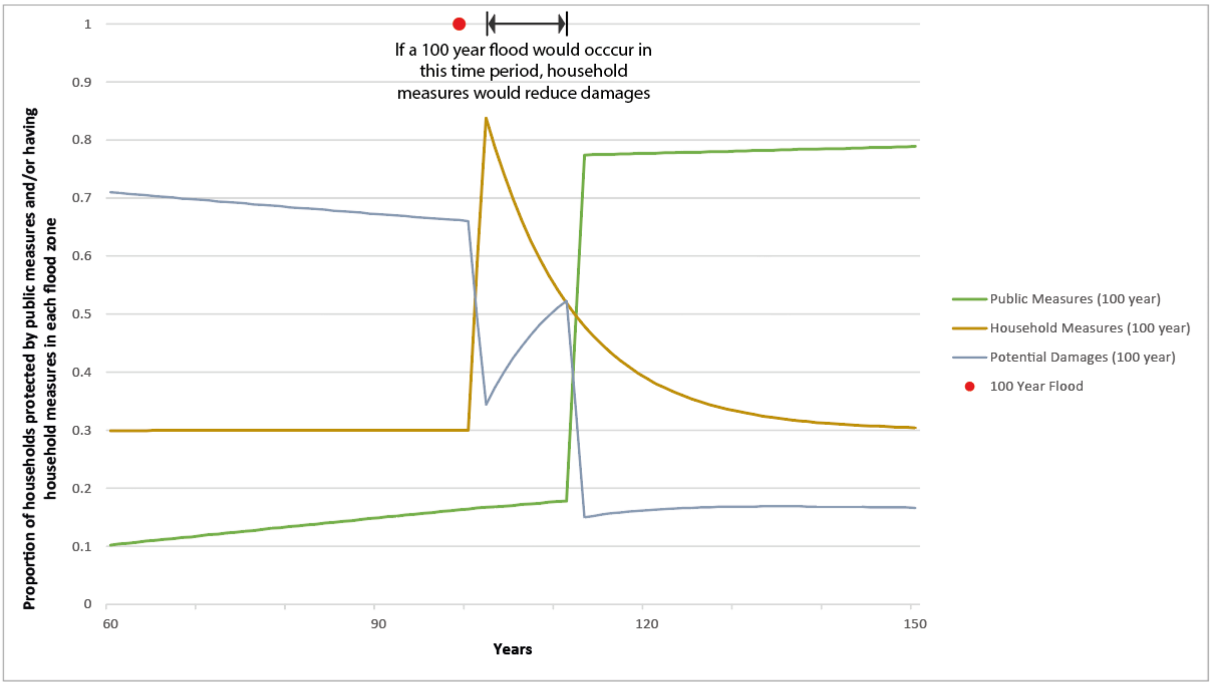


Figure 8 Potential damages, household and public protection measures in the 100 year flood risk zone for the "baseline" scenario, showing how household measures go up directly after a flood event and reduce the potential damages in the event of a subsequent flood in the period of time before public measures are implemented.

5.2 Climate change

In a scenario whereby floods occur twice as frequently, yet all other conditions remain the same as in the baseline, flood management measures are implemented sooner (Fig. 9). If the first flood occurs at 50 years, rather than 100 years in the 100 year flood zone, the model suggests that the first damages to be experienced are larger at 50 years, than they would be at 100 years. This is because at the time of the first large flood, there has been less time to prepare through the steady implementation of public measures, achieved through Advanced Support. This is important, because it suggests, that if advancements in flood risk management through technological and institutional changes proceed at the current rate, but the next large flood occurs sooner than would otherwise be expected (due to climate change driven hydrological conditions), there will be slightly higher damages than could have been anticipated if a flood would occur at a point in time further in the future. At the same time, the post-disaster response to a large flood that occurs sooner than could otherwise be expected, will incur costs for implementing future public flood measures at an earlier point in time than would be expected without climate change. These aspects of i) a lower level of prior preparedness, and ii) earlier future implementation of measures following flooding, highlight clearly two financial implications of climate change induced increased flood frequencies.

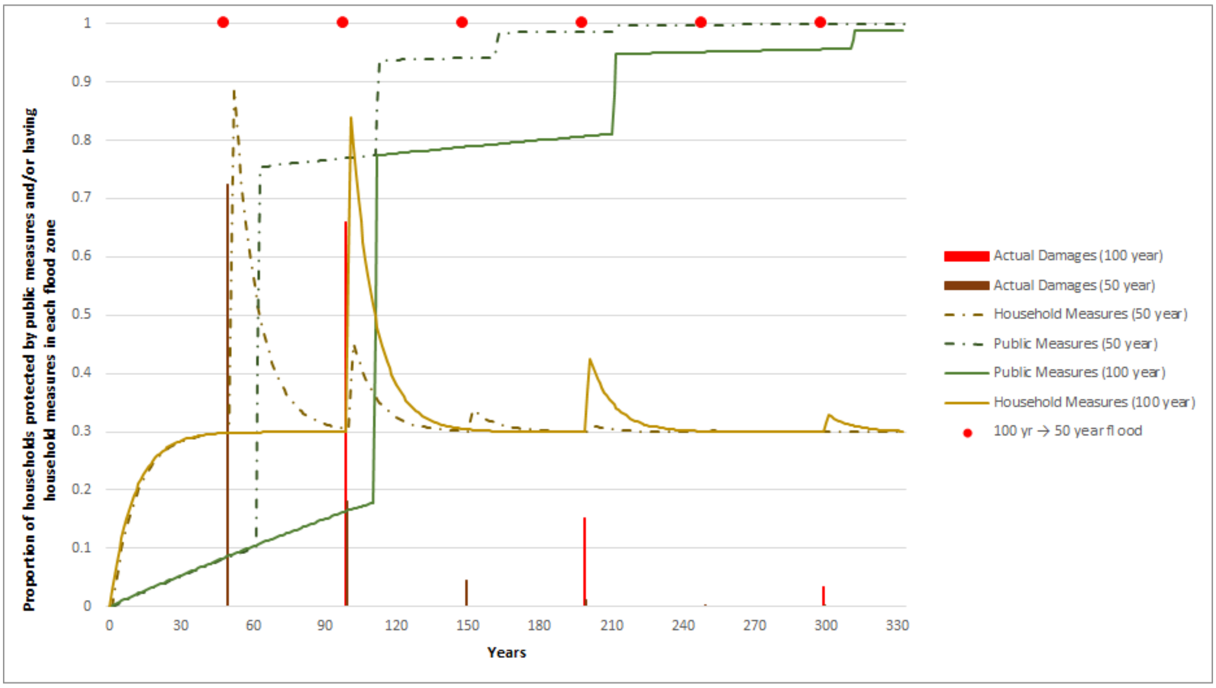


Figure 9 Comparison between damages and implementation of household and public measures in the 100 year flood risk zone for the “baseline” scenario and for the “climate change” scenario whereby the 100 year flood occurs twice as frequently.

5.3 Increase in Advanced Resources to support Public Measures

The modelling suggests that doubling Advanced Resources (from 0.01 in the Baseline to 0.02) would lead to public measures being implemented more rapidly in the 30 year flood zone and therefore damages during flooding would be lower relative to the baseline. After one flood in the 30 year flood zone, public measures become fully implemented, eliminating future flood damages in the 30 year flood zone. A tenfold increase in advanced resources in the 100 year flood zone (from 0.001 to 0.01) more than halves the damages at the first flood relative to the baseline. The model also suggests, if actual damages in the 300 year flood zone should be brought close to zero by 300 years in the future, the current resource allocation to support public measures would have to be increased by a factor of 100, relative to the Baseline.

5.4 Increase Public Support for Household Measures

In order to increase the number of households with private measures, publicly funded support could raise householders’ coping appraisal and capacity to implement measures. The model suggests that increasing the support to householders tenfold (from 0.03 in the Baseline to 0.3), will lead to a higher proportion of households with at least one household measure from 0.3 in the baseline, to 0.8, across all flood zones (Fig. 5). This ultimately has an impact on reducing flood damages for the first 100 year flood experienced by approximately 30%, from 0.66 in the baseline to 0.38 (Fig. 6).

5.5 Limits to Public Measures

While increasing advanced resources for Public Measures would reduce damages, there are usually a range of limitations, including financial, technical and political, that prevent public measures being implemented and/or maintained. This is simulated by reducing Advanced Resources by a factor of 100, and Reactive response ($\alpha_{PM_{Pro}}$) by a factor of 100 compared to the baseline and reducing the parameter for operation and maintenance from 0.01 (in the baseline) to 0.0001. Unsurprisingly, modelling a scenario where public measures are limited, shows how damages for the 30 and 100 year floods are considerably higher (up to almost 0.8) (Fig. 6e) than in the baseline.

5.6 Off-set Limits to Public Measures with Support for Household Measures

It is interesting to consider whether additional support for household measures could off-set the damage that result when public measures remain unimplemented or are disbanded. From a policy perspective, information on how costly it is to promote private preparedness in order to substitute a withdrawal of public effort would be of interest. Modelling shows that increasing support for Household Measures by a factor of 10 could reduce damages below those of the Baseline (Fig. 6f.) for the first 30 and 100 year flood. The oscillations in the Damages reflect the rapid implementation of household measures following each flood and then their subsequent, fairly rapid, decay. This means that for each flood, the same extent of damages are experienced. This suggests that reducing the decay rate through additional support for operation and maintenance of household measures (conceptually, in a similar way to the operation and maintenance of public measures) would be a priority to achieve a long-term reduction in damages. However, even if all properties implemented household measures, damage related impacts from inundation would always remain at 0.3 because, in this model, the upper limit to the maximum reduction in damages from household measures has been set at 70% (Table 2). Exploring ways to increase the capacity of household measures to minimise damages would also be a priority.

6. Strengths, limitations and future work

The main strength of the modelling process is the structured abstraction of the complex interactions between flood damages, public measures and private measures. There are many different analysis approaches that can be taken to examine process interactions, but the numerically based, systems-dynamics approach demands the researcher to split the complex system into components and make explicit the relationships and feedbacks by identifying parameters and assigning them values. By specifically examining the coupling between floods and human responses, the work highlights that while the experience of flood damage does drive the implementation of household and public measures, perceived threat of flooding plays a limited role in stimulating private protection measures at the household level. Instead, external public support increases household coping appraisal, which is subsequently translated into an increased uptake of household measures. Coping appraisal is also disconnected from flood experience and damage. The inclusion of external drivers in a human-flood interaction model therefore seems to be essential and future socio-hydrological work needs to pay closer attention to which elements should be internalised (and lead to self-regulating behaviour) and those which should be externalised (and enable the system to be manipulated). Often these aspects expand well beyond the hydrological system requiring socio-hydrological models to extend their peripheries.

The model offers insights that align with mainstream paradigms. These include that climate change will lead to more damages and costs, and that household measures can decrease vulnerability and reduce damages in places where public measures are yet to be implemented, or where they are insufficient to reduce flood exposure. These outcomes reflect the assumptions that are put into the model, and also include that in Austria, the coverage of public measures is slowly but steadily increasing, flood events boost public prioritisation and spending on measures, and therefore measures to reduce the impacts of large floods that are yet to be encountered are still to be implemented.

Criticisms of systems dynamics based socio-hydrological models often argue that model findings generate circular observations that reflect the assumptions that are put into the model (Krueger and Alba, 2022). It is worth highlighting that models can only ever reflect the assumptions that are put into them and therefore any model that reveals previously “unknown” relationships or dynamics suggests a model structural issue worthy of critical inspection. It is however important to note that dynamic models can reveal “unexpected” behaviour, because they can project the basic assumptions of the present, which can be identified quite reliably, to the future, which is very much more difficult to anticipate (Forrester et al., 1974). For this reason, any socio-hydrological modelling endeavour must focus on understanding and making transparent the grounding for the assumptions that are being made, including self-reflection on the modellers’ position and influences (Carr et al., 2020; Krueger et al., 2016).

Can this model have value for policy and practice? The graphical depictions generated by this model enable the narrative to be visualised, for instance showing the potential scale of damages due to limits to public measures in the event of a rare, high magnitude flood. This stylised model can highlight that to avoid these damages, there is a need for continual investment in integrated flood risk management. Basic estimates on the benefits of investing in public or household measures can be drawn from this work. However, its lumped nature does not enable it to say which private measures should be implemented and the nature of the support (direct funding to householders or local level initiatives to raise householders capacity to implement measures). The critical next step would be calibrating this model with a historical time series of flood damages and public and private flood responses. Resources to pull such a data set together from different sources are therefore needed to advance this work. Additional longitudinal data would also enable processes and their interactions to be better defined. For example, this work uses an exponential decay rate for public and household measures that may be neither optimal or even accurate. As longitudinal studies and analysis from the social and engineering sciences advance process understanding on degradation and decay, these aspects of the model can be substantially improved. Furthermore, this work employs constant parameters that do not change through time or due to feedbacks in the system, for example, the reactive parameters could perhaps be expected to respond more strongly if more severe damages are experienced (Barendrecht et al., 2021).

Stochastic flood events and their stochastic damages (e.g. Wagenaar et al., 2016), or even stochastic social drivers, such as changes in advanced resources or public support, are not modelled here. These additional layers of complexity could be added, but it is first important to consider whether the process interactions are sufficiently well understood that adding in variability to the external drivers adds valuable. In more confined systems, in which the process interactions are well understood, such as public health models, an agent based modelling approach whereby the interactions between each agent is stochastic in nature, has been shown to generate additional information on the variability in possible outcomes in comparison to the deterministic approach of the systems-dynamics model (Macal, 2010). Developing human-flood models at the agent-based scale can generate model outcomes that include differences between households that impacts their ability to implement measures (e.g. their different social, human and economic capitals) and which may be able to move modelling human-water systems into the realm of prediction of short term outcomes, similarly to that of public health modelling. However, the level of certainty in understanding the process interactions should determine when stochastic approaches are applied.

7. Conclusions

The outcomes from this work concern the three aspects of improving understanding of the interactions between flooding and public and private responses. Through the highly iterative process of developing a conceptual model based on established theory and then testing it with empirical data, it became clear that flood damages are an important, but not the only, driver for the implementation of household measures, that flood damages do increase perceived threat of flooding, but that perceived threat of flooding does not seem to have a substantial role as a driver for household measures. External factors are expected to play a key role in driving both public and private protection measures and need to be integrated into models.

By further developing the model to a dynamic model, through determining a number of simple and constant parameters, it becomes possible to explore how the system may change through time. This process requires explicit assumptions about public-private flood interactions to be stated and generalisations to be made in order to generate expected system behaviour. The benefits of these generalisations are that graphical depiction of the narratives can be made through the modelling and outcomes can be visualised. These include the adaptation effect, whereby household measures are quickly implemented after a flood event and can reduce damage if a subsequent flood happens in the time period before public measures have been implemented. This adaptation effect however, is likely to have a rapid rate of decay that perhaps could be minimised through focussed interventions. Modelling suggests that extra support for household measures could raise the proportion of properties in the flood risk zone with household measures, and this would lead to a reduction in flood damages in the 100 and 300 year flood zone where public measures are either unavailable or yet to be implemented. Finally, the model shows that climate change that leads to a large flood occurring sooner than could otherwise be expected, could lead to higher costs because i) at the current rate of implementation, adequate measures will not be in place before the large event occurs and damages will be large, and ii) following the event, measures will be implemented that would, without climate change, be implemented at a later point in time, meaning that costs will come sooner.

8. References

Aerts, J. C. J. H., Botzen, W. J. W., Emanuel, K., Lin, N., de Moel, H., and Michel-Kerjan, E. O. (2014) Evaluating Flood Resilience Strategies for Coastal Megacities, Science, 344, 473–475, https://doi.org/10.1126/science.1248222, 2014.

Aerts, J.C.J.H. (2018) A Review of Cost Estimates for Flood Adaptation. *Water*, *10*, 1646. https://doi.org/10.3390/w10111646

Aerts, J.C.J.H., Botzen, W.J., Clarke, K.C. et al. (2018) Integrating human behaviour dynamics into flood disaster risk assessment. Nature Climate Change 8, 193–199. https://doi.org/10.1038/s41558-018-0085-1

Alderman, K., Turner, L.R., Tong, S. (2012) Floods and human health: A systematic review, Environment International, 47, 37-47, https://doi.org/10.1016/j.envint.2012.06.003.

Babcicky P., and Seebauer S., (2017) The two faces of social capital in private flood mitigation: opposing effects on risk perception, self-efficacy and coping capacity, Journal of Risk Research, 20:8, 1017-1037, DOI: 10.1080/13669877.2016.1147489

Babcicky, P., & Seebauer, S. (2019). Unpacking protection motivation theory: Evidence for a separate protective and non-protective route in private flood mitigation behavior. Journal of Risk Research, 22(12), 1017–1037.

Babcicky, P., Seebauer, S. (2020). Collective efficacy and natural hazards: Differing roles of social cohesion and task-specific efficacy in shaping risk and coping beliefs. Journal of Risk Research, 23(6), 695-712. doi:10.1080/13669877.2019.1628096.

Babcicky, P., Seebauer, S., Thaler, T. (2021) Make it personal: Introducing intangible outcomes and psychological sources to flood vulnerability and policy. International Journal of Disaster Risk Reduction, 58, 102169, https://doi.org/10.1016/j.ijdrr.2021.102169.

Barendrecht, M. H., Viglione, A., Kreibich, H., Merz, B., Vorogushyn, S., & Blöschl, G. (2019). The value of empirical data for estimating the parameters of a sociohydrological flood risk model. Water Resources Research,55, 1312–1336. https://doi.org/10.1029/ 2018WR024128

Barendrecht, M.H., McCarthy, S. and Viglione, A. (2021) A comparative analysis of the relationship between flood experience and private flood mitigation behaviour in the regions of England. J Flood Risk Management. 14:e12700. https://doi.org/10.1111/jfr3.12700

Barendrecht, M.H., Viglione, A., Blöschl, G. (2017) A dynamic framework for flood risk. Water Security, 1, 3-11, https://doi.org/10.1016/j.wasec.2017.02.001.

Bertola, M., Blöschl, G., Bohac, M. et al. (2023) Megafloods in Europe can be anticipated from observations in hydrologically similar catchments. Nat. Geosci. 16, 982–988. https://doi.org/10.1038/s41561-023-01300-5

Blöschl G., Hall J., Parajka J., Perdigão R. A. P., Merz B., et al. (2017) Changing climate shifts timing of European floods. Science, 357 (6351), 588–590. doi:10.1126/science.aan2506.

Blöschl, G., Hall, J., Viglione, A., Perdigão, R.A.P., Parajka, J., et al. (2019) Changing climate both increases and decreases European river floods. Nature, 573, 108-111. doi: 10.1038/s41586-019-1495-6

Blöschl, G., Waser, J., Buttinger-Kreuzhuber, A. et al. (2022) HOchwasserRisikozonierung Austria 3.0 (HORA 3.0). Österr Wasser- und Abfallw 74, 212–223. https://doi.org/10.1007/s00506-022-00848-7

Bubeck, P., Botzen, W. J. W., & Aerts, J. C. J. H. (2012). A review of risk perceptions and other factors that influence flood mitigation behavior. *Risk Analysis*, 32(9), 1481-1495.

Carr, G., Barendrecht, M. H., Balana, B. B., & Debevec, L. (2022). Exploring water quality management with a socio-hydrological model: a case study from Burkina Faso. Hydrological Sciences Journal, 67(6), 831–846. https://doi.org/10.1080/02626667.2021.2020276

Ciullo, A., Viglione, A., Castellarin, A., Crisci, M., & Di Baldassarre, G. (2017). Socio-hydrological modelling of flood-risk dynamics: Comparing the resilience of green and technological systems. Hydrological Sciences Journal, 62(6), 880–891. https://doi.org/10.1080/02626667.2016.1273527

Crick, F., Jenkins, K., Surminski, S. (2018) Strengthening insurance partnerships in the face of climate change – Insights from an agent-based model of flood insurance in the UK. Science of The Total Environment, 636, 192-204, https://doi.org/10.1016/j.scitotenv.2018.04.239.

Di Baldassarre, G., et al., (2013). Socio-hydrology: conceptualising human flood interactions. Hydrology and Earth System Sciences, 17 (8), 3295– 3303. doi:10.5194/hess-17-3295-2013

Dottori, F., Szewczyk, W., Ciscar, JC. et al. Increased human and economic losses from river flooding with anthropogenic warming. Nature Clim Change 8, 781–786 (2018). https://doi.org/10.1038/s41558-018-0257-z

Du, S.Q. , P. Scussolini, P.J. Ward, M. Zhang, J.H. Wen, L.Y. Wang, E. Koks, A. Diaz-Loaiza, J. Gao, Q. Ke, J.C.J.H. Aerts (2020) Hard or soft flood adaptation? Advantages of a hybrid strategy for Shanghai Glob. Environ. Chang., 61, 102037

Dubbelboer, J., Nikolic, I., Jenkins, K., Hall, J. (2017) An agent-based model of flood risk and insurance, Journal of Artificial Societies, 20.

Few, R. (2003). Flooding, vulnerability and coping strategies: Local responses to a global threat. Progress in Development Studies, 3(1), 43–58.

Forrester, J. W. (1985). "The" model versus a modeling "process." *System Dynamics Review, 1*(1), 133-134. doi: 10.1002/sdr.4260010112

Forrester, J. W., Low, G. W., & Mass, N. J. (1974). The debate on World Dynamics: A response to Nordhaus. *Policy Sciences, 5*(2), 169-190. doi: 10.1007/bf00148039

Fothergill, L.J., A.S. Disney, E.E. Wilson (2021) A qualitative exploration of the psychological impacts of living with the uncertainty of persistent flood risk, Public Health, 198, 141-145, https://doi.org/10.1016/j.puhe.2021.07.016.

Fuchs, S., Röthlisberger, V., Thaler, T., Zischg, A., Keiler, M., 2017. Natural hazard management from a coevolutionary perspective: Exposure and policy response in the European Alps. Annals of the American Association of Geographers 107 (2), 382–392. https://doi.org/10.1080/24694452.2016.1235494.

Grothmann, T. and Patt, A. (2005) Adaptive capacity and human cognition: The process of individual adaptation to climate change. Global Environmental Change, 15, (3), 199-213, https://doi.org/10.1016/j.gloenvcha.2005.01.002.

Haer, T., T. G. Husby, W.J.W. Botzen, J.C.J.H. Aerts (2020) The safe development paradox: An agent-based model for flood risk under climate change in the European Union, Global Environmental Change, 60, 102009, https://doi.org/10.1016/j.gloenvcha.2019.102009.

Haer, T., W.J.W Botzen, J.C.J.H. Aerts (2019) Advancing disaster policies by integrating dynamic adaptive behaviour in risk assessments using an agent-based modelling approach. *Environ. Res. Lett.* 14 (4) 044022. doi: 10.1088/1748-9326/ab0770

Hall, J. W. (2019). Socio-hydrology in perspective—Circa 2018. Water Resources Research, 55, 1776–1777. https://doi.org/10.1029/2019WR024870

Hanger-Kopp, S., Thaler, T., Seebauer, S., Schinko, T., and Clar, C. (2022). Defining and operationalizing path dependency for the development and monitoring of adaptation pathways. Global Environ. Change 72, 102425. https://doi.org/10.1016/j.gloenvcha. 2021.102425.

Harries, T. (2012). The anticipated emotional consequences of adaptive behaviour – Impacts on the take-up of household flood-protection measures. Environment and Planning A, 44(3), 649–668

Hayden, F. G. (2019). Modeling System Complexity in the Context of Geopolitics Related to Climate Change. *Journal of Economic Issues*, *53*(2), 545–552. https://doi.org/10.1080/00213624.2019.1603770

ivoni, M., & Perl, A. (2020). Rethinking Transport Infrastructure Planning to Extend Its Value over Time. Journal of Planning Education and Research, 40(1), 82-91. https://doi.org/10.1177/0739456X17741196

JBA, (2013) Establishing the Cost Effectiveness of Property Flood Protection: FD2657. Final Report. Department for Environment Food and Rural Affairs, London. https://assets.publishing.service.gov.uk/media/6038e0cad3bf7f03985e129d/Establishing_the_Cost_Effectiveness_of_Property_Flood_Protection_Technical_Report.pdf

Johnson, L., Mikulewicz, M., Bigger, P., Chakraborty, R., Cunniff, A., Griffin, P.J., Guermond, V., Lambrou, N., Mills-Novoa, M., Neimark, B.., Nelson, S., Rampini, C., Sherpa, P., Simon, G. (2023) Intervention: The invisible labor of climate change adaptation. Global Environmental Change, 83, 102769, https://doi.org/10.1016/j.gloenvcha.2023.102769.

Kam, P.M., Aznar-Siguan, G., Schewe, J., Milano, L., Ginnetti, J., Willner, S., McCaughey, J.W., and Bresch, D.N. (2021) Global warming and population change both heighten future risk of human displacement due to river floods. Environ. Res. Lett. 16, 044026. doi: 10.1088/1748-9326/abd26c

Kim, Y., Carvalhaes, T., Helmrich, A., Markolf, S., Hoff, R.., Chester, M., Li, R., Ahmad, N. (2022) Leveraging SETS resilience capabilities for safe-to-fail infrastructure under climate change, Current Opinion in Environmental Sustainability, 54, 101153, https://doi.org/10.1016/j.cosust.2022.101153.

Kreibich, H. and Thieken, A.H. (2009) Coping with floods in the city of Dresden, Germany. Nat Hazards 51(3):423–436.

Kreibich, H., Bubeck, P., Van Vliet, M., & De Moel, H. (2015) A review of damage reducing measures to manage fluvial flood risks in a changing climate. Mitigation and Adaptation Strategies for Global Change, 20(6), 967e989.

Kreibich, H., Van Loon, A.F., Schröter, K. et al. (2022) The challenge of unprecedented floods and droughts in risk management. Nature 608, 80–86. https://doi.org/10.1038/s41586-022-04917-5

Krueger, T., Alba, R. (2022) Ontological and epistemological commitments in interdisciplinary water research: Uncertainty as an entry point for reflexion, Frontiers in Water, 4, 10.3389/frwa.2022.1038322

Kuhlicke C, Seebauer S, Hudson P, et al. (2020) The behavioral turn in flood risk management, its assumptions and potential implications. WIREs Water. 2020;7:e1418. https://doi.org/10.1002/wat2.1418

Kuhlicke, C., Scolobig, A., Tapsell, S. et al. (2011) Contextualizing social vulnerability: findings from case studies across Europe. Nat Hazards 58, 789–810. https://doi.org/10.1007/s11069-011-9751-6

Macal, C. M. (2010) To agent-based simulation from system dynamics. In B. Johansson, S. Jain, J. Montoya-Torres, J. Hugan & E. Yücesan (Eds.) Proceedings of the 2010 Winter Simulation Conference (pp. 371–382), December 5–8, 2010. Baltimore, MD: IEEE.

Mazzoleni, M., & Brandimarte, L. (2023): Modelling flood awareness in floodplain dynamics, Hydrological Sciences Journal, DOI: 10.1080/02626667.2023.2177543

Mees, H. L. P., Driessen, P. P. J., & Runhaar, H. A. C. (2012). Exploring the Scope of Public and Private Responsibilities for Climate Adaptation. Journal of Environmental Policy & Planning, 14(3), 305–330. https://doi.org/10.1080/1523908X.2012.707407

Mitter, H., Martin Schönhart, Manuela Larcher, Erwin Schmid, (2018) The Stimuli-Actions-Effects-Responses (SAER)-framework for exploring perceived relationships between private and public climate change adaptation in agriculture, Journal of Environmental Management, 209, 286-300, https://doi.org/10.1016/j.jenvman.2017.12.063.

Nordbeck, R., Steurer, R., and Löschner, L. (2019) The future orientation of Austria's flood policies: from flood control to anticipatory flood risk management, Journal of Environmental Planning and Management, 62:11, 1864-1885, DOI: 10.1080/09640568.2018.1515731

Rauter, M., Kaufmann, M., Thaler, T., Fuchs, S. (2020) Flood risk management in Austria: Analysing the shift in responsibility-sharing between public and private actors from a public stakeholder's perspective, Land Use Policy, 99, 105017, https://doi.org/10.1016/j.landusepol.2020.105017.

Rentschler, J., Avner, P., Marconcini, M. et al. (2023) Global evidence of rapid urban growth in flood zones since 1985. Nature 622, 87–92 https://doi.org/10.1038/s41586-023-06468-9

Rentschler, J., Salhab, M. & Jafino, B.A. (2022) Flood exposure and poverty in 188 countries. Nat Commun 13, 3527 https://doi.org/10.1038/s41467-022-30727-4

Sairam, N., Schröter, K., Lüdtke, S., Merz, B., & Kreibich, H. (2019) Quantifying flood vulnerability reduction via private precaution. Earth's Future, 7, 235–249. https://doi.org/10.1029/2018EF000994

Schlögl, M., Fuchs, S., Scheidl, C., Heiser, M. (2021) Trends in torrential flooding in the Austrian Alps: A combination of climate change, exposure dynamics, and mitigation measures, Climate Risk Management, 32, 100294, https://doi.org/10.1016/j.crm.2021.100294.

Seebauer, S. and Babcicky, P. (2020), The Sources of Belief in Personal Capability: Antecedents of Self-Efficacy in Private Adaptation to Flood Risk. Risk Analysis, 40: 1967-1982. https://doi.org/10.1111/risa.13531

Seebauer, S. and Babcicky, P. (2021), (Almost) all Quiet Over One and a Half Years: A Longitudinal Study on Causality Between Key Determinants of Private Flood Mitigation. Risk Analysis, 41: 958-975. https://doi.org/10.1111/risa.13598

Seebauer, S., Thaler, T., Hanger-Kopp, S. et al. (2023) How path dependency manifests in flood risk management: observations from four decades in the Ennstal and Aist catchments in Austria. Reg Environ Change 23, 31 https://doi.org/10.1007/s10113-023-02029-y

Sivapalan, M., and G. Bloeschl (2015) Time scale interactions and the coevolution of humans and water, Water Resour. Res., 51, 6988–7022, doi:10.1002/2015WR017896.

Thaler, T. (2021) Social justice in socio-hydrology—how we can integrate the two different perspectives. Hydrol. Sci. J., 1-10. doi: 10.1080/02626667.2021.1950916

Tonn, G.L. and Guikema, S.D. (2018), An Agent-Based Model of Evolving Community Flood Risk. Risk Analysis, 38: 1258-1278. https://doi.org/10.1111/risa.12939

van Valkengoed, A.M., Steg, L. (2019). Meta-analyses of factors motivating climate change adaptation behaviour. Nature Climate Change, 9(2), 158-163. doi: 10.1038/s41558-018-0371-y.

Viglione, A., Di Baldassarre, G., Brandimarte, L., Kuil, L., Carr, G., Salinas, J.L., Scolobig, A. and Blöschl, G. (2014) Insights from socio-hydrology modelling on dealing with flood risk – roles of collective memory, risk-taking attitude and trust. Journal of Hydrology, 518 71–82. doi: 10.1016/j.jhydrol.2014.01.018

Wagenaar, D. J., de Bruijn, K. M., Bouwer, L. M., and de Moel, H. (2016) Uncertainty in flood damage estimates and its potential effect on investment decisions, Nat. Hazards Earth Syst. Sci., 16, 1–14, https://doi.org/10.5194/nhess-16-1-2016, 2016.

Wesselink, A., Kooy, M., & Warner, J. (2017). Socio-hydrology and hydrosocial analysis: Toward dialogues across disciplines. WIREs Water, 4, e1196.

Zeitoun, M., Lankford, B., Krueger, T., Forsyth, T., Carter, R., Hoekstra, A.Y., Taylor, R., Varis, O., Cleaver, F., Boelens, R., Swatuk, L., Tickner, D., Scott, C.A., Mirumachi, N., and Matthews, N. (2016) Reductionist and integrative research approaches to complex water security policy challenges, Global Environmental Change, 39, 143-154, https://doi.org/10.1016/j.gloenvcha.2016.04.010.

Zhuo, L. and Han, D. (2020) Agent-based modelling and flood risk management : a compendious literature review. Journal of Hydrology, 591. 125600. ISSN 0022-1694