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# Advancing disaster policies by integrating dynamic adaptive behaviour in risk assessments using an agent-based modelling approach

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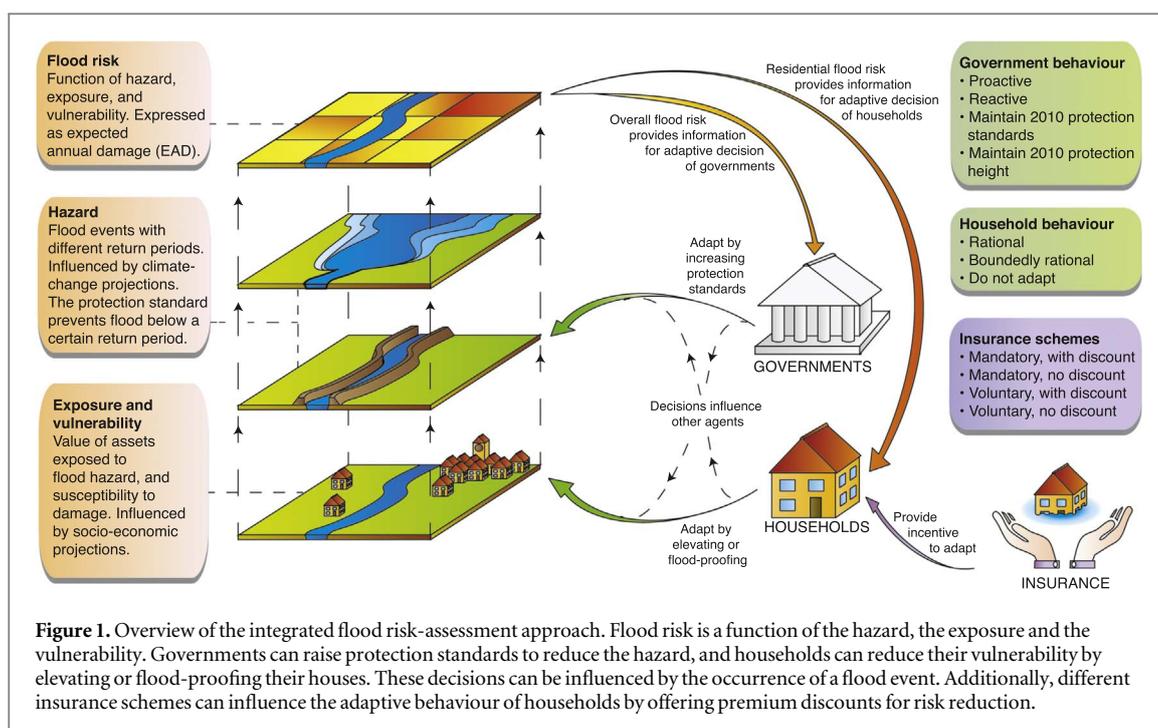
Toon Haer<sup>1,2,5</sup> , W J Wouter Botzen<sup>1,3,4</sup> and Jeroen C J H Aerts<sup>1,2</sup><sup>1</sup> Institute for Environmental Studies, Vrije Universiteit Amsterdam, 1081HV Amsterdam, The Netherlands<sup>2</sup> Deltares, Delft, The Netherlands<sup>3</sup> Utrecht University School of Economics (U.S.E.), Utrecht University, 3584EC Utrecht, The Netherlands<sup>4</sup> Risk Management and Decision Processes Center, The Wharton School, University of Pennsylvania, United States of America<sup>5</sup> Author to whom any correspondence should be addressed.E-mail: [toon.haer@vu.nl](mailto:toon.haer@vu.nl)**Keywords:** adaptation, flood risk, agent-based modelsSupplementary material for this article is available [online](#)**Abstract**

Recent floods in the United States and Asia again highlighted their devastating effects, and without investments in adaptation, the future impact of floods will continue to increase. Key to making accurate flood-risk projections are assessments of how disaster-risk reduction (DRR) measures reduce risk and how much risk remains after adaptation. Current flood-risk-assessment models are ill-equipped to address this, as they assume a static adaptation path, implying that vulnerability will remain constant. We present a multi-disciplinary approach that integrates different types of adaptive behaviour of governments (proactive and reactive) and households (rational and boundedly rational) in a continental-scale risk-assessment framework for river flooding in the European Union. Our methodology demonstrates how flood risk and adaptation might develop, indicates how DRR policies can steer decisions towards optimal behaviour, and indicates how much residual risk remains that has to be covered by risk-transfer mechanisms. We find that the increase in flood risk due to climate change may be largely offset by adaptation decisions. Moreover, we illustrate that adaptation by households may be more influential for risk reduction than government protection in the short term. The results highlight the importance of integrating behavioural methods from social sciences with quantitative models from the natural sciences, as advocated by both fields.

**1. Introduction**

Recent losses caused by hurricanes Florence and Mangkhut and the large-scale floods in India demonstrate that extreme flood events can have devastating effects on economies and human society. Without global investments in adaptation supported by scientific projections of risk, the future impact of floods will continue to increase in many regions due to climate change [1] and socio-economic growth [2]. This is why adaptation, disaster-risk reduction (DRR) and mechanisms for coping with loss and damages (L&D) were high on the agenda during the COP23 in Bonn [3]. Key to making accurate projections are assessments of how DRR measures reduce risk over time [4], the

potential of policies and regulations to steer DRR [4], and estimations of the risk that remains after DRR [5]. Current large-scale flood-risk-assessment models are often ill-equipped to address these issues, as they assume a static adaptation path, thereby implying that vulnerability remains constant over time [6–11], as if the main agents in risk management, such as governments, neither adapt to, nor learn from, flood events and do not anticipate increased risk over time. In reality, there is an interplay between the adaptive behaviour of governments, the adaptive behaviour of individuals, and the flood risk environment, as changes in one influences the other [12–14]. Recent studies in the field of socio-hydrology have developed novel methods to capture and explain the dynamics resulting from the



feedbacks between hydrological, technical and social processes, stressing the importance of this interplay [12–18]. However, these do not yet capture the role of individual households, despite the fact that the aggregate effect of household behaviour can significantly influence trends in flood risk and vulnerability [19, 20]. In line with the emerging field of socio-hydrology that aims to describe the relationship between social and hydrological systems [12–17], we present a multi-disciplinary modelling approach, combining methods from the natural and social sciences that integrate (individual) adaptive behaviour dynamics from both the government and households in a continental-scale risk-assessment framework for river flooding in the European Union (EU). By applying a multi-agent model, we (1) quantitatively demonstrate how flood risk and adaptation might develop, (2) demonstrate how risk changes if adaptation of governments and households is steered towards economical optimal behaviour, for instance through DRR policies, and (3) estimate the residual risk after adaptation that has to be covered by insurance or other risk-transfer mechanisms for L&D policies. Our approach is transferable to other natural disasters, and encompasses local to continental scales.

## 2. Methods and materials

### 2.1. Model summary

Economic flood risk is typically modelled as a function of the hazard, the exposure of assets, and the vulnerability of assets to flood events, but with static assumptions about adaptive behaviour [1, 21, 22]. Here, we apply this flood-risk framework in a modelling study that integrates the dynamic adaptive

behaviour of governments and EU households, as illustrated in figure 1.

The model illustrated in figure 1 and depicted schematically in supplementary material figure S1 (available online at [stacks.iop.org/ERL/14/044022/mmedia](https://stacks.iop.org/ERL/14/044022/mmedia)) estimates fluvial flood risk for the period 2010–2080 at annual time steps. To better represent future flood risk, we integrate the adaptive behaviour of governments and households in the risk-assessment approach. We focus on risk to both urban and rural residential buildings to illustrate the effects of household (micro-) adaptation on large-scale risk and government (macro-) adaptation. The current fluvial flood risk is calculated by using current climate and socio-economic conditions to represent the hazard and the exposure (supplementary material sections 3–5). Current protection standards are based on the global database of FLOOD PROTECTION STANDARDS [23] (supplementary material section 2). To simulate future risk, we use the flood hazard data [2, 22, 24] for two representative concentration pathways (RCPs), and the data [25] of two shared socio-economic pathways (SSPs) to project exposure (supplementary material sections 3–4). RCP's provide time-dependent projections of atmospheric greenhouse gases which are used in flood hazard modelling, and SSP provide among others quantitative projections of change in population growth and GDP which are used here as exposure data. To represent a change in residential building surface relevant for elevating and dry-proofing, we developed a method to represent how change in SSPs affects the spatial-temporally explicit change in residential building surface, and hence, the exposure of urban and rural residential areas to floods (supplementary material section 5). Although in principle

**Table 1.** Combinations of household and government behaviour types for which the model is run.

Combination of behaviour types	Household behaviour type	Government behaviour type
1	Rational households	Proactive governments
2	Rational households	Reactive governments
3	Boundedly rational households	Proactive governments
4	Boundedly rational households	Reactive governments
5	Households do not adapt	2010 protection heights
6	Households do not adapt	2010 protection standards

all RCPs can be linked to all SSPs, we run the model for two scenario combinations [2, 26] that represent a lower and upper boundary to climate change: RCP2.6-SSP1 and RCP8.5-SSP5. On the basis of risk information, (future) stochastic flood events that mimic the influence of extreme events (supplementary material section 6), and the cost of adaptation, households and governments take adaptation decisions that influence flood risk to residential buildings in both urban and rural areas.

The adaptive behaviour of households (supplementary material section 7) follows a model of subjective, discounted expected utility (DEU), which is the mainstream theory of economic decision-making under risk. Based on the DEU, residential agents—who either have rational or boundedly rational risk perceptions—decide for each time step either to flood-proof existing buildings (that is, by dry-proofing, which reduces damage by preventing water from entering the building) or to elevate newly developed buildings (that is, by raising the structure above potential flood levels) [27]. Both elevation and dry-proofing are adaptive behaviours by households that reduce the risk to the residential building surface. In addition, we assess the effect of incentives from different insurance schemes on residential behaviour and DRR, namely, voluntary or mandatory insurance, with or without risk-based premium discounts to incentive DRR. The discount on the premium can be offered to those households that have insurance, to motivate them to reduce their risk by implementing loss-reducing measures (supplementary material section 8).

Finally, government agents, representing EU member states, dynamically decide to increase protection standards by raising dikes based on a cost-benefit analysis (CBA) [28] of the total fluvial flood risk and the costs of increasing dyke heights (supplementary material section 9). Governments can be proactive or reactive.

Modelling uncertainties regarding input data and the modelling framework are described in the supplementary material section 10.

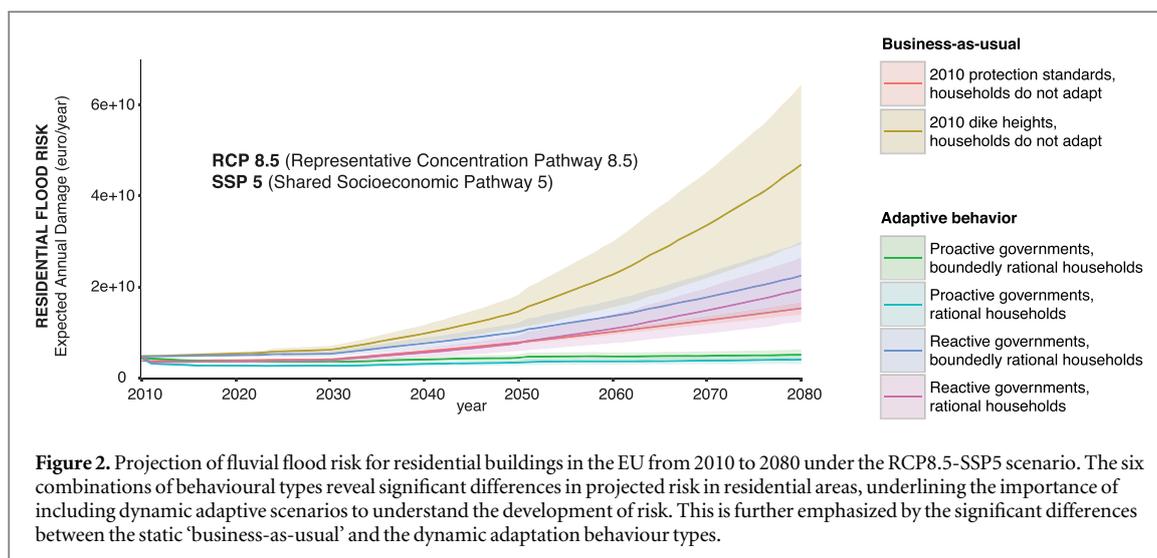
## 2.2. Comparing behaviour

We assess the effects of six different combinations of government and household behavioural types in flood-risk assessments, which cover a wide range of (uncertain) responses to future risk, see table 1.

Adaptive behavioural types include the following: EU households who are either rational or boundedly rational, and governments that are either proactive or reactive (supplementary material section 1). Rational households are fully informed about the risks they face, and their decisions to reduce their vulnerability by flood-proofing, by elevating their homes or by taking out flood insurance, are based on objective calculated risk. By contrast, boundedly rational households generally underestimate risk if no flood occurs. Directly after a flood, risk perceptions becomes high, causing overestimation of risk. In subsequent years, after a flood, risk perceptions decline to prior levels over approximately six years (for details see supplementary material section 7). Both proactive and reactive governments base their decisions on CBA, only the timing differs. Proactive governments invest in increasing flood protection to reduce potential hazards in regular cycles, while reactive governments decide to take action only after a flood event has struck a region. While proactive governments and rational households might display economically desirable behaviour, reality reveals that governments more often act reactively [1, 29] and that households often behave in a boundedly rational manner [30]. Note that for this large-scale study we focus on three adaptive measures (elevating new buildings, flood-proofing existing buildings, and flood protection with dykes), as they are often cost-effective [27]. Other measures are also available, such as wet-proofing buildings, nature-based solutions (e.g. creating wetlands to buffer floods), and constructing reservoirs.

In addition, we provide a brief analysis of the influence of financial incentives on adaptive measures. For instance, offering a discount on insurance premium when households reduce their risk may stimulate the adaptive decisions of households (supplementary material section 8). While the effect of incentives to reduce risk is not the main focus of this study, the additional analysis shows the potential of the methodology to explore the effect of such incentives, and shows that these incentives could indeed be effective in stimulating risk reduction.

To illustrate the importance of our approach, we compare flood-risk simulations that include the four combinations of dynamic behaviours with two more commonly applied static behavioural approaches [6–11]. In the first static combination, neither



**Figure 2.** Projection of fluvial flood risk for residential buildings in the EU from 2010 to 2080 under the RCP8.5-SSP5 scenario. The six combinations of behavioural types reveal significant differences in projected risk in residential areas, underlining the importance of including dynamic adaptive scenarios to understand the development of risk. This is further emphasized by the significant differences between the static ‘business-as-usual’ and the dynamic adaptation behaviour types.

governments nor households take additional measures to reduce vulnerability or hazard, and dyke-protection heights remain at 2010 levels (‘2010 protection height’). In the second combination, governments invest in extra flood protection when risk increases, to maintain the 2010 protection standard, but households do not take additional measures (‘2010 protection standards’). Note that this implies in reality that governments are proactive, but as the protection standards are static, we do not consider this scenario as ‘proactive’ with respect to modelling dynamic behaviour.

As an example of the static approaches, in the ‘2010 protection standards’ combination, the current 100 year protection standard continues to protect against a future 100 year flood even if the flood hazard increases due to climate change. In contrast, in the first static combination (i.e. ‘2010 protection height’), the height of the river dykes does not change with increasing flood hazard, and therefore protection standards decline with increasing flood volumes due to climate change.

### 3. Results

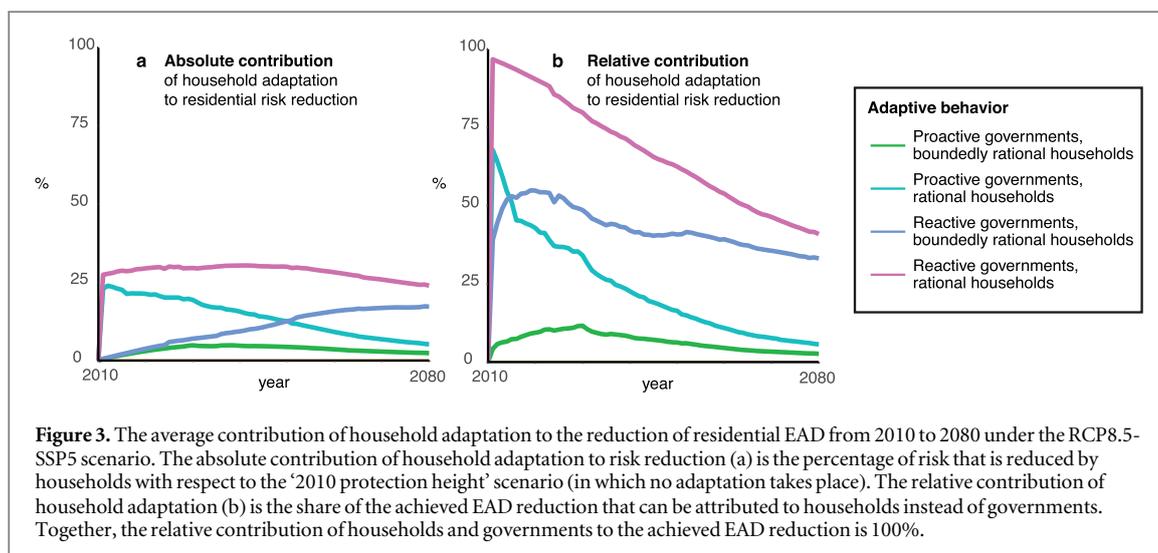
#### 3.1. How adaptive behaviour shapes risk

Our modelling study demonstrates that including dynamic adaptive behaviour in flood-risk assessments leads to substantial differences in projected residential flood risk for the EU, as illustrated here for the future RCP8.5-SSP5 scenario (figure 2) and in the supplement for the RCP2.6-SSP1 scenario (supplementary material figure S5). As an illustration, compared to the static ‘2010 protection height’ behavioural type that is usually applied in flood-risk management studies, the residual risk to residential buildings is on average 35%–50% lower after 2030 if households adapt in a boundedly rational or rational manner, respectively, and governments adapt reactively. If governments adapt proactively, the risk is even 72%–79% lower.

With respect to the static ‘2010 protection standards’ behavioural type, projections indicate an increase in risk of 6%–35% after 2030 if households adapt in a rational or boundedly rational manner, respectively, and governments adapt reactively. Even though adaptation takes place, it is not enough to offset the impact of climate change. However, projections for rational or boundedly rational households indicate a decrease in risk of 46%–59% if governments adapt proactively. These differences demonstrate that the dynamic adaptation of households and governments can lead to significantly different levels of residual risk that should be covered by L&D policies.

Furthermore, the difference between reactive and proactive government behaviour illustrates the potential benefit of macro-level DRR policies, such as the EU flood directive [31]. Our results indicate that a transition from a reactive to a proactive approach can reduce the risk by between €3.1 billion and €6.7 billion per year in 2050 and by between €14.4 and €18.5 billion per year in 2080.

Moreover, figure 3 demonstrate the significance of including the behaviour of households in terms of flood risk for the future RCP8.5-SSP5 scenario and in the supplement for the RCP2.6-SSP1 scenario (supplementary material figure S5). Aggregating the effect of rationally behaving households can reduce roughly up to 25% of the residential flood risk in the EU. Boundedly rational households, who in general underestimate risk, reduce risk by between 5% and 20%. While proactive governments are responsible for a large share in risk reduction compared to households, the relative share of risk reduction taken on by both rational and boundedly rational households largely outweighs the relative share taken on by reactive governments (figure 3). When households are rational while governments act reactively, they are projected to take on a relative share of more than 50% of the risk reduction over the period 2010–2080, and more than 75% in the initial years 2010–2040. If they are instead



boundedly rational, they are still projected to take on a relative share of roughly 50% of the risk reduction.

It should be noted that the absolute risk reduction for proactive governments is higher than that for reactive governments (figure 2). However, even when governments are proactive, the results indicate that rational households can have a substantial share in the risk reduction (figure 3). When the government is proactive, and households are rational, households are projected to take on a relative share in risk reduction of more than 25% for the period until 2050. When instead the households are boundedly rational, the relative share is between 10% and 20%, as the proactive governments take on most of the risk reduction (figure 3). This highlights the importance and the possible manoeuvre space for adaptation policies to stimulate individual households to act in a more rational manner—for instance, through financial incentives that stimulate cost-effective DRR investments [30].

### 3.2. Behaviour and climate change projections

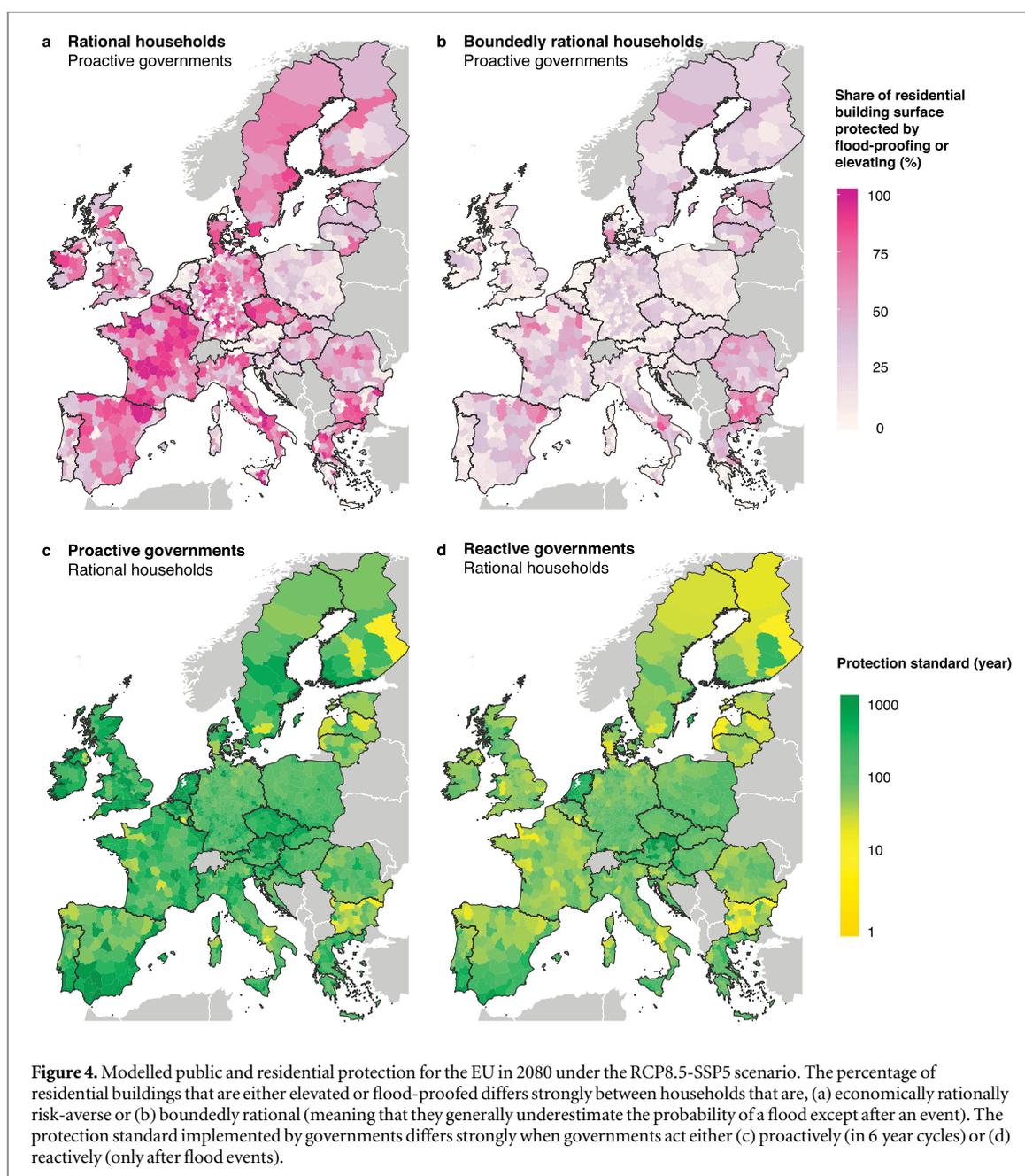
Our results also indicate that including dynamic adaptive behaviour can outweigh the effects of climate change scenarios in our risk projections. When households adapt either in a rational or boundedly rational fashion and governments act proactively, flood risk for the RCP8.5-SSP5 scenario is 17%–37% lower in the period after 2030 than in the RCP2.6-SSP1 scenario with static ‘2010 protection standard’ behaviour types. Under similar conditions but instead compared to the ‘2010 protection height’ baseline, flood risk is 55%–66% lower than in the RCP2.6-SSP1 scenario (supplementary material figure S5). Even if governments adapt reactively under the RCP8.5-SSP5 scenario, the resulting flood risk is as low as in the RCP2.6-SSP1 scenario with the static ‘2010 protection height’ baseline. As we illustrate in supplementary material table S6 for the EU member states, the spread in risk under different behaviour types overlaps between the RCP2.6-SSP1 and RCP8.5-SSP5 scenarios. With these

modelling results, we argue that, depending on the behaviour of governments and households, the behavioural signal will potentially outweigh the climate change signal in flood risk projections.

### 3.3. Interaction of behaviour and policy

Figure 4 depicts a spatial representation of the percentage of buildings in flood-zones that is protected by elevating or dry-proofing, and the achieved protection standards in the year 2080. Both depictions assume the RCP8.5-SSP5 scenario. On a micro level, the rational behaviour of households leads, on average over all regions, to 27% higher protection rates than boundedly rational behaviour. The model results show that the effect of rational adaptation on risk reduction by households is large throughout the EU, but it is smaller for countries that already have very high protection standards, such as the Netherlands. Although government protection in Poland is lower, it is still relatively high with respect to the residential value exposed to floods, and residential protective activity is consequently low. This inverse relationship between government protection and household protective behaviour holds across countries, and is stronger when households are boundedly rational (supplementary material figure S9). Other countries such as Austria also exhibit low residential protective activity, but here it is caused by declining risk. The above conclusions are similar for other scenarios and behaviour types (supplementary material figures S10–13).

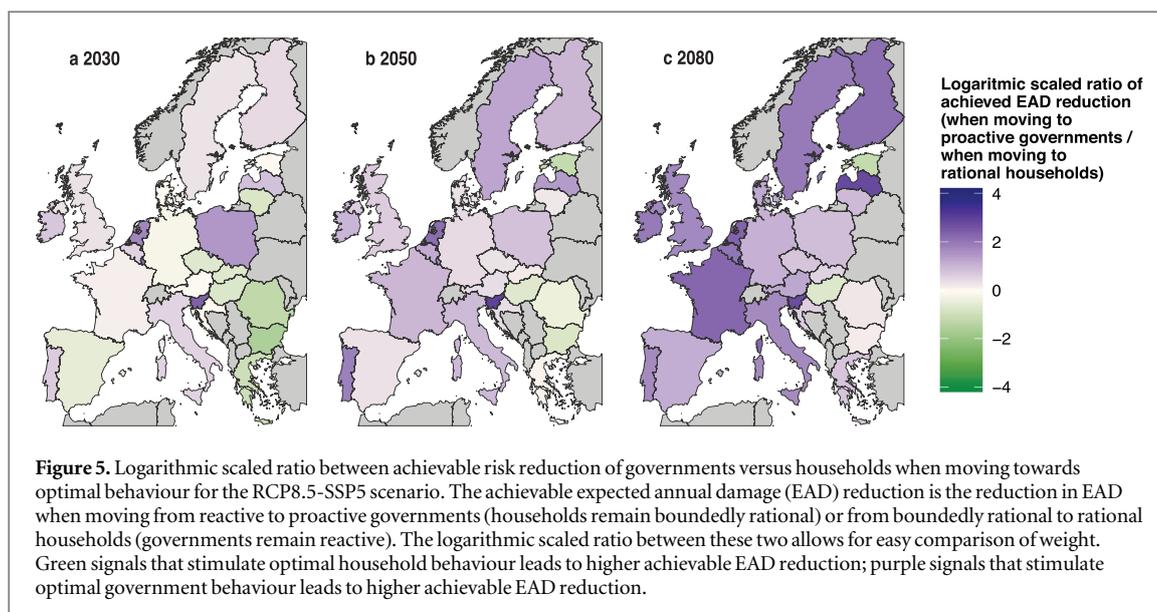
Figure 4 also indicates that proactive behaviour by governments leads to stepwise upgrading of flood-protection standards, while a reactive course leads to a decline in flood-protection standards and a consequent increase in risk. While the benefits of a proactive course are persistent throughout Europe, figure 4 indicates that it is especially important in flood-prone regions such as western Europe and parts of central and southern Europe. These projections emphasize



the importance of pushing proactive DRR policies, as is done by the EU Flood Directive [31].

Our results also support the design of financial incentives (e.g. through insurance) to stimulate DRR by households—for instance, by offering discounts on flood insurance premiums if loss-reducing measures are implemented [30]. However, such insurance schemes need to be well designed to lead to effective behaviour changes and, for example, depend on whether the purchase of flood insurance is voluntary or mandatory. Our additional analysis indicates that boundedly rational households are not inclined to buy insurance in the first place if insurance is voluntary, as they underestimate risk (supplementary material figure S8) and hence cannot receive a discount on an insurance premium as they have none. Consequently,

boundedly rational households do not increase DRR in a scenario where insurance offers discounts (supplementary material figure S7). By contrast, when flood insurance is mandatory and a discount is offered, boundedly rational households increase the implementation of DRR measures. The discount leads to, on average, 38% more risk reduction by boundedly rational households, compared the scenario in which households do not receive a premium discount (supplementary material figure S7). While the design of effective and viable insurance schemes is complex [32–34], our analysis provides insights into the interplays between insurance incentives and behavioural effects with respect to DRR, which underlines the importance of including behavioural aspects when developing insurance schemes.



### 3.4. Comparing risk reduction by governments and households

To prioritize DRR, it is relevant to assess what combination of adaptation by governments and households is most effective. Figure 5 illustrates how risk reduction can be achieved by government moving from being reactive to being proactive versus risk reduction achieved by stimulating households to act rationally instead of boundedly rationally (see also supplementary material tables S7–10). For many countries, stimulating rational household behaviour through 2030 will be more effective to achieve risk reduction than moving to more proactive government protection strategies. This is especially true for south-eastern European countries, where the expected damages are lower. However, even in countries with high flood exposure (Germany and the UK), stimulating rational residential behaviour through 2030 household will be equally effective as moving to proactive government protection. With further increasing risk towards 2050 and 2080, risk reduction by governments starts to outweigh the achievable risk reduction by households for most EU member states. This is especially visible in western European countries such as the Netherlands, Belgium, France, and the UK, where large-scale infrastructure can effectively protect high-value areas.

## 4. Discussion and conclusion

The recent flood disasters in the US and Asia, and the projections of increasing climate risks and extreme events, again demonstrate the urgent need to improve disaster-reduction policies, as underlined by the international agreement on L&D [35] and the Sendai Framework for DRR [36]. Such policies rely on accurate risk-assessment methods. Our multi-disciplinary modelling approach which includes

behavioural adaptation offers a tool to significantly improve quantitative assessments of risk and adaptation [5]. Scientific advances in modelling complexity and human behaviour cover decades of work, and although there is no real consensus about what method fits a certain application best [37], it is commonly agreed that human behaviour is often neglected in quantitative risk-assessment approaches in the environmental sciences [13, 38]. Uncertainty regarding modelling projections remains due to a lack of empirical research into the influence of human decision-making on vulnerability over time, especially in face of low-probability/high-impact events. While we base our modelling on established economic models of behaviour and empirical data from surveys, additional empirical research is required to calibrate and validate the complex adaptive behaviour and the influences of for instance different risk perceptions. Nonetheless, by focusing on established flood-risk-assessment models and integrating established behavioural theories, our study indicates that individual behaviour indeed plays an important role in risk trends.

Our methods—which are transferable to other regions and other natural hazards such as storm surges, extreme winds, and earthquakes—provide a means to quantitatively analyse the potential manoeuvre space for DRR policies, taking into account dynamic decision-making processes. Moreover, our study provides a method to project the residual risk that needs to be covered by L&D policies, for instance through flood insurance mechanisms [32]. Not only can flood insurance cover risk, but as demonstrated here, households can be stimulated via premium discounts to implement DRR measures at the building level. This could also aid in alleviating the increased stress on existing compensation mechanisms, such as the EU Solidarity Fund [6].

Although this study captures some key processes and agents in dynamics adaptation, future research may explore dynamic behaviour in more detail [12–14]. For instance, emerging cross-basin, cross-country cooperation's, such as the International Commission for the Protection of the Rhine can have a positive influence on adaptation strategies. Cities, which are increasingly developing their own adaptation strategies (e.g. C40, National League of Cities), could prove to be an important agent to include. For these future efforts, we stress the importance of integrating the aggregate potential of individual adaptive behaviour that DRR policies could tap into. Thus, it is imperative for DRR research to shift its focus toward integrating individual adaptive behaviour and interactions with the main stakeholders involved in DRR [5].

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