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The safe development paradox: An agent-based model for flood risk under climate change in the European Union

Toon Haer[a,*], Trond G. Husby[b], W.J. Wouter Botzen[a,c,d], Jeroen C.J.H. Aerts[a]

[a] Institute for Environmental Studies, Vrije Universiteit Amsterdam, De Boelelaan 1087, 1081HV, Amsterdam, the Netherlands
[b] Netherlands Environmental Assessment Agency (PBL), The Hague, the Netherlands
[c] Utrecht University School of Economics (U.S.E.), Utrecht University, Utrecht, the Netherlands
[d] Risk Management and Decision Processes Centre, The Wharton School, University of Pennsylvania, USA.

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ABSTRACT

With increasing flood risk due to climate change and socioeconomic trends, governments are under pressure to continue implementing flood protection measures, such as dikes, to reduce flood risk. However, research suggests that a sole focus on government-funded flood protection leads to an adverse increase in exposure as people and economic activities tend to concentrate in protected areas. Moreover, governmental flood protection can reduce the incentive for autonomous adaptation by local households, which paradoxically results in more severe consequences if an extreme flood event occurs. This phenomenon is often referred to as the 'safe development paradox' or 'levee effect' and is generally not accounted for in existing flood risk models used to assess developments in future flood risk under climate change. In this study we assess the impact of extreme flood events for the European Union using a large-scale agent-based model (ABM). We quantify how the safe development paradox affects (1) population growth and the increase in exposed property values, (2) the reduction in investments to flood-proof buildings as public protection increases, and (3) the increase in potential damage should a flood occur. For this analysis, we apply an ABM that integrates the dynamic behaviour of governments and residents into a large-scale flood risk assessment framework, in which we include estimates of changing population growth. We find that the impact of extreme flood events increases considerably when governments provide high protection levels, especially in large metropolitan areas. Moreover, we demonstrate how policy that stimulates the flood-proofing of buildings can largely counteract the effects of the safe development paradox.

1. Introduction

In the past decade, floods in Europe have affected over 4 million inhabitants and their assets, killing almost a thousand people and leaving over five thousand homeless (Guha-Sapir et al., 2017). The 2013 floods alone, which affected most of Central Europe, resulted in reported damages of 18 billion euro. During the period of 2006 – 2013 over two hundred minor and major flood events cost a total of 52 billion euro in reported damages (Guha-Sapir et al., 2017). These already dire numbers are expected to be aggravated by an increase in extreme events due to climate change (IPCC, 2012), and a growth of exposed assets due to socio-economic developments (Jongman et al., 2012). The high risk from flooding has prompted the creation of several policy frameworks such as the Sendai Framework for Disaster Risk Reduction (UN, 2015), the Warsaw International Mechanism for Loss and Damage (UNFCCC, 2013), and the EU Floods Directive (EU, 2007). These frameworks attempt to emphasize a holistic risk reduction approach, where governments, institutions and households are all responsible for reducing risk. However, in practice the situation often differs because in many countries dikes and other large engineering structures remain the prevailing flood risk management strategies (Harries and Penning-Rowsell, 2011; Hartmann and Spit, 2016).

Even though these large engineering structures are often cost-effective, they lead to the 'promise of protection' (Hartmann and Spit, 2016), which creates a sense of safety among those who reside in the protected area. This sense of safety can lead to adverse effects, where, for instance, self-reliance and the reduction of local-scale vulnerability (e.g. through flood-proofing buildings) is neglected (IPCC, 2012). Moreover, development in low-lying areas is often accelerated after the installation of flood protection (Burby, 2006; Baldassarre et al., 2013; Ludy and Kondolf, 2012; Sivapalan et al., 2012). Paradoxically, this means that the reduction of hazard

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[*] Corresponding author.
E-mail address: toon.haer@vu.nl (T. Haer).

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probability through increasing flood protection may lead to an increase in exposure and vulnerability. Subsequently, if a flood disaster strikes then its consequences are more severe than they would have been otherwise (Baldassarre et al., 2018; IPCC, 2012). This process, first described by White (1942), is often referred to as 'the safe development paradox' (Burby, 2006), the 'levee effect' (Tobin, 1995) or the 'dike paradox' (Hartmann and Spit, 2016). We adopt the term safe development paradox in this paper.

Several recent studies focusing on population growth have analysed how the safe development paradox increases population growth in protected areas, and, in contrast, decreases population growth in areas where a flood has recently occurred (Burby, 2006; Collenteur et al., 2015; Husby et al., 2014). Other studies have used a conceptual approach to study the mechanisms of the safe development paradox (Baldassarre et al., 2018; Baldassarre et al., 2013; Sivapalan et al., 2012). Although the effects of flood protection on population growth are well known, current scientific models for flood risk projections rarely address the safe development paradox, and as such do not provide a realistic assessment of the impact of extreme events (Baldassarre et al., 2018; Baldassarre et al., 2018).

This knowledge gap is partly caused by the common exclusion of micro-level behaviour from flood risk assessments, such as adaptation efforts by households (Aerts et al., 2018). Neglecting micro-level behaviour reduces the capacity of analytical frameworks to quantify the risk reduction potential of policies that counteract the effects of the safe development paradox. For instance, a solution to the paradox might be found in building-level protection measures that reduce the impact of extreme events, such as wet-proofing (i.e. reducing damage while still allowing water to enter) and dry-proofing (i.e. reducing damage by preventing the entry of water) of buildings, or elevation (i.e. reducing damage by raising structures). When dikes fail or are overtopped, such building-level measures can greatly reduce the damage done by extreme events, as shown by Kreibich et al. (2005) and Poussin et al. (2015). Accordingly, the integration of micro-level decision-making in flood risk assessments is important to quantify the effects of the safe development paradox, and to guide policy makers in their decision-making.

In this study we provide a quantitative assessment of the safe development paradox by applying an augmented agent-based model (ABM) developed by Haer et al. (2019), which integrates the dynamic adaptive behaviour of both governments and EU residents in a large-scale flood risk assessment model. The reasons for applying an ABM, are that we aim to capture the system outcome of the safe development paradox resulting from the autonomous adaptation decisions from a highly heterogenous population of households, which for example differ with respect to their risk situation, value of houses, costs of adaptation measures, and flood experience. An ABM approach is especially useful for capturing this heterogeneous behaviour through different behavioural rules that range from rational to boundedly rational behaviour. Moreover, ABMs are suitable for modelling interactions in behaviour. In our application households decisions interact with the autonomous adaptation decision by heterogenous government agents throughout Europe that, for example, depend on the risk situation and the initial level of protection, and also follow different behavioural rules ranging from proactive to reactive, and include building codes, or policies that stimulate households to act more rational. Our study adds to a growing field of ABM applications in flood risk analysis, which focussed on evacuation (Dawson et al., 2011), climate change migration (Hassani-Mahmooei and Parris, 2012), housing markets (Filatova et al., 2011; Filatova et al.,2009) and community mitigation (Dubbelboer et al., 2017; Jenkins et al., 2017; Tonn and Guikema, 2017). In particular, the ABM includes a new module that estimates the change in population growth resulting from either increased public protection or flood events. With this, we can show how the safe development paradox affects population growth and the resulting increase in exposed property values. Moreover, we analyse the fall in demand for building-level investments as public protection increases, and the resulting increase in damage should a flood occur. We also demonstrate how this safe development effect can be largely counteracted by steering the behaviour of residents towards economically desirable behaviour, for instance by providing financial incentives for flood-proofing buildings. Our work contributes to the policy design of EU member states under the EU Floods Directive.

2. Model approach

We use and augment the model developed by Haer et al. (2019), which incorporates the dynamic adaptive behaviour of governments and households into a flood hazard model, and returns the monetary expression of yearly average flood risk in the form of the expected annual damage (EAD) for the entire EU (for a detailed model description including relevant changes, see supplementary material A. For the original model see https://iopscience.iop.org/1748-9326/14/4/044022/media/erl_14_044022_sd.pdf). Building on the work of Haer et al. (2019), we integrate a new algorithm into the model, which accounts for the change in population growth (Burby, 2006; Collenteur et al., 2015; Husby et al., 2014) as a result of flood occurrence and increased governmental protection (Section 2.3.2). Additionally, in this study we examine the absolute flood impact for different return periods in the form of expected damage (ED). This augmented ABM can thus be used to analyse the consequences of the safe development paradox. To clarify the difference between the EAD and ED, we assume a hypothetical situation where one 100-year flood occurs and produces damage X; then the ED would be X given the absolute damage, and the EAD would be X/100 to produce a yearly average damage. In reality, the EAD is calculated by taking the integral over all flood return periods, i.e., all calculated ED values.

Moreover, with this ABM setup we can quantify how well-intended proactive government strategies can lead to lower flood risk (EAD) but higher impacts of extreme events (ED) as households become less inclined to take protective efforts. This is shown schematically in Fig. 1. For the purpose of clarity, we discuss the model in Sections 2.1–2.4 and highlight the augmentations, details are discussed in Supplementary Material A. In the model, during each one-year time-step, the flood hazard and associated EAD and ED change dynamically and flood events occur stochastically (Section 2.1), socio-economic change affects exposed value and population, and population growth causes an increase in residential building surface and exposed value (Section 2.1). Moreover, governments can adapt by raising protection standards (Section 2.2), and residents can adapt by either dry-proofing or elevating residential buildings (Section 2.3). By modelling the adaptive responses of both governments and residents, we can analyse the interactions and feedbacks between the adopted protective strategies.

2.1. Flood risk and flood impact

Flood inundation maps for the set of return periods (5-, 10-, 25-, 50-, 100-, 250-, 500- and 1000-year return periods) are developed on a 30”x30” resolution following the GLOFRIS modelling cascade (Haer et al., 2019; Ward et al., 2013; Winsemius et al., 2013). As this study focuses on behaviour and not on climate change scenarios, we show the results for Representative Concentration Pathway (RCP) 8.5 in the main text and the RCP2.6 scenario in Supplementary Material B. Each 30”x30” cell has a specific exposed value based on the land use class, country, and share of residential building surface (Haer et al., 2019). The ED for each return period is calculated for each 30”x30” grid cell as the product of the inundation depth in each cell, the exposure, and the depth – damage curve. The latter variable describes the relation between inundation depth and damage to the value of exposure (de Moel et al., 2015; Merz et al., 2010; Ward et al., 2013). The EAD is then determined by approximating the integral over the ED of all return periods (de Moel et al., 2015; Merz et al., 2010; Ward et al., 2013).

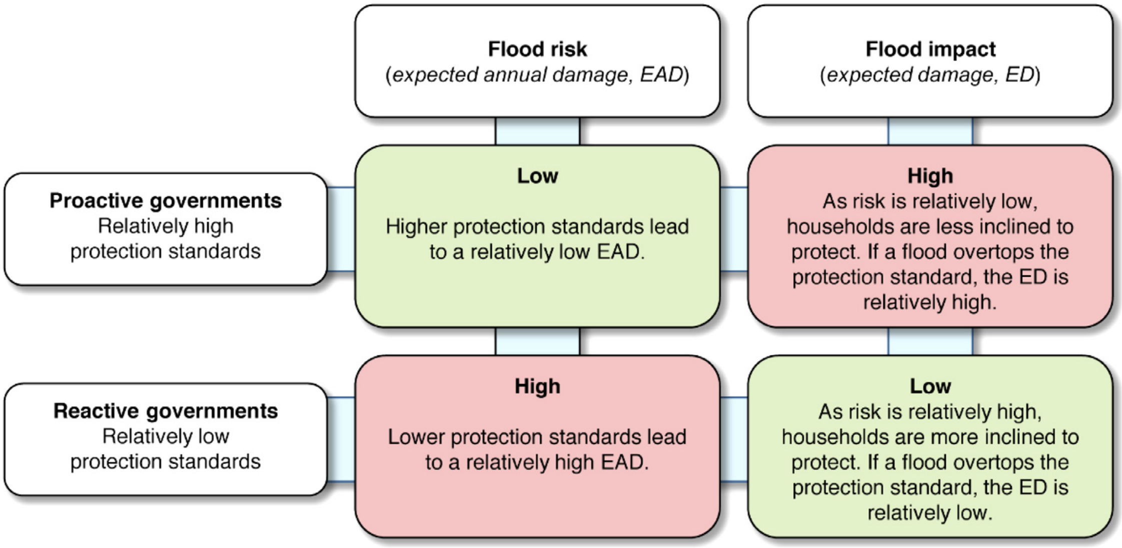

Fig. 1. Schematic representation of the safe development paradox in relation to the protective behaviour of governments and households.

The exposed residential building area and the value it represents follows a spatial-temporal function that estimates residential building surface based on population levels (Haer et al., 2019). The yearly change in population levels initially follows socio-economic pathway (SSP) data at 30”x30” resolution (Haer et al., 2019; van Vuuren et al., 2007). While in principle all SSPs can be coupled to all RCPs, we provide estimates of the lower and upper bounds by coupling the RCP2.6 pathway to the SSP1 pathway, and the RCP8.5 pathway to the SSP5 pathway. Under the baseline settings, population levels − and therefore exposed residential building surface − are unaffected by the occurrence of a flood and the construction of a dike. This assumption is common in risk assessments, although it disregards the influence of flood events and increased protection on population growth observed in the literature (Burby, 2006; Collenteur et al., 2015; Husby et al., 2014). In Section 2.3.2 we describe a new methodology that integrates changes in population growth as a result of flood occurrences or increased government protection.

The ED is further influenced by the adaptive behaviour of governments and residents (Sections 2.2 and 2.3). Moreover, to be able to model reactive behaviour, flood events occur stochastically in model runs, with a probability associated with the return period: for example, the yearly stochastic probability p associated with a 100-year return period is 0.01.

2.2. Government decision-making

Governments can adapt through separate government agents in each NUTS 3 region by increasing dike heights to raise protection standards. Initial protection standards and dike heights at t = 0 (2010) are derived from the FLOPROS database (Haer et al., 2019; Scussolini et al., 2016). The decision to raise protection standards is based on a cost−benefit analysis (CBA), calculated for each 30”x30”grid cell and summed for the NUTS 3 region, which follows in stylized form (for details see Haer et al., 2019):

$$\mathrm{NPV}_{PS_i} = \sum_{t=1}^{L} \frac{B_{t,PS_i} - C_{t,PS_i}}{(1+r)^t} - C_{0,PS_i} \tag{1}$$

The net present value *NPV* is calculated for protection standards *PS* that protect against a return period i over the lifespan of a dike L. We use a lifespan of 100 years, similarly to Aerts et al. (2014). The benefit $B_{t,PSi}$ is the net EAD reduced, i.e., the EAD reduced by the evaluated protection standard PS_i minus the EAD reduced by the current protection standard $PS_{current}$. The additional yearly maintenance costs $C_{t,PSi}$ are the net maintenance cost of raising the protection standard PS_i above the current protection standard $PS_{current}$. The investment costs $C_{0,PSi}$ represent the initial cost of increasing the dike height. We use a discount rate r of 4%, in line with the recommended discount rate in the EU[1]. Time lags between decision and implementation are not explicitly considered. We model two behaviour scenarios that represent current and optimal behaviour; one in which governments are reactive, and decide whether or not to increase protection standards only after a flood occurs; and a scenario in which governments are proactive, and decide whether or not to increase protection standards in six-year cycles. These approaches are representative of currently observed behaviour (Adger et al., 2005; Albright, 2011; IPCC, 2012; Johnson et al., 2005) and desirable optimal behaviour. The latter approach is similar to the one taken by the government in the Netherlands, which is currently one of the most proactive governments concerning flood risk reduction (Kind, 2014). As both approaches are based on CBA, proactive governments are more likely to raise protection standards and are thus potentially more subjected to the safe development effects of dike construction on population levels and the adaptive behaviour of households than reactive governments.

2.3. Household decision-making

2.3.1. Adaptation decision

The adaptive behaviour of households in each 30”x30” grid cell follows a discounted expected utility (DEU) model, which represents mainstream economic theory for decision-making under risk. At each time-step households compare the DEU of two strategies: implementing loss-reducing measures, and doing nothing. The strategy that yields the highest DEU is executed. The evaluation of DEU is performed separately for existing unprotected building surface, which residents can dry-proof, and newly developed building surface, which residents can elevate. This approach is taken as dry-proofing is the most cost-effective measure for existing buildings, while elevating is the cost-effective measure for newly developed buildings. Dry-proofing reduces 85% (Aerts and Botzen, 2011) of the damage done to existing dry-proofed residential building surface, while elevating shifts the depth−damage curve upwards by 1 m for the existing elevated residential building surface in a grid cell. The stylized form of the DEU is as follows:

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[1] http://ec.europa.eu/smart-regulation/guidelines/tool_54_en.htm.http://ec.europa.eu/smart-regulation/guidelines/tool_54_en.htm.http://ec.europa.eu/smart-regulation/guidelines/tool_54_en.htm

$$DEU_{str} = \int_{p_i}^{p_I} \beta p_i U(EAB_{str}) dp \tag{2}$$

The *DEU* is calculated for the two different strategies *str* as the integral over the probabilities *p* associated with each return period *i*, and the utility of the expected annual benefits *EAB* of the strategy *str*. The calculation is done over the lifespan of the measure (75 years for dry-proofing and 100 years for elevation, see supplementary material A). As the probability of a flood event can be reduced over time by government decision-making (Section 2.2), the decision made by households is also influenced by government action. This can lead to the safe development paradox, where households do not act as protection is already provided. Budget constraints are not explicitly taken into account. The utility function follows $U(x) = \ln x$ (Haer et al., 2016). The $\beta = 10^{2\alpha_t - 1}$ represents how perceived flood probabilities deviate from objective probabilities, where $\alpha_t = 1$ if a flood occurs in the NUTS 3 region where residents live, and $\alpha_t = \alpha_{t-1} / 1.6$ if no flood occurs. This represents boundedly rational households that overestimate the probability of a flood if one has just occurred, and that begin to underestimate the probability of a flood in periods where no flood occurs (Haer et al., 2016). This behaviour is often observed in reality (Kunreuther, 1996; Kunreuther et al., 1985). We also run the model for $\beta = 1$, causing Eq. (2) to reflect a rational, risk-averse decision process where the perceived risk is equal to the objective risk. The rational, risk-averse decision process reflects households that are not influenced by underestimation or overestimation, and that have perfect knowledge of the risk situation. Such behaviour can be stimulated, for instance, by providing incentives to correct for boundedly rational behaviour, as explained further in Section 2.4.

2.3.2. *Spatiotemporal population dynamics*

We also model the change in population growth (i.e. households moving in or out of the area) resulting from flood occurrence or increased protection (Baldassarre et al., 2015). Previous ABMs have included the location decision explicitly (Tonn and Guikema, 2017), but such studies are often forced to implement ad hoc decision rules due to a lack of empirical data for calibration and validation. On a small scale, studies by Filatova et al. (2015, 2011) show how ABMs can be combined with empirical data to model, for instance, the urban housing market, which is influenced by risk and steered by the presence of local amenities. However, as large-scale empirical data needed to derive behavioural rules is often missing, we choose to model the location decision implicitly based on empirical results and applied to the EU. We do so by adjusting the percentage growth as given by the SSP (Section 2.1) with the marginal impact on population growth from flood events and increased protection, as empirically determined by Husby et al. (2014) (Table 1). Husby et al. (2014) carried out a so-called dynamic difference-in-difference statistical analysis on municipality-level population data of the Netherlands for the period 1960 − 2000. This study offers the only empirical data for changes in population growth that result from both flood occurrence and increased protection, as far as we are aware. In this difference-in-difference analysis, Husby et al. (2014) compared population growth in areas that were affected by increased public protection with population growth in areas that were not affected, with the use of municipality-level census data. Note that the change in population growth influences the exposed value, and thus potentially increases EAD and ED. However, an increase in exposed value could also lead to increased protective efforts by governments (Section 2.2) and households (Section 2.3.1), and can thus indirectly reduce EAD and ED. As such, including the effect on population represents a neutral change with respect to the adaptive behaviour.

We use the results of Husby et al. (2014) as a proxy for other EU countries. To address the uncertainty associated with extrapolating population growth dynamics of the Netherlands to Europe, we assume that for any given country the growth effects in a specific year lie within the triangular distribution of the estimate found for the Netherlands. Clearly, the marginal effect of protection and flooding on population growth varies in both time and space, and there are uncertainties around both the shape and the median of the distribution. The strategy employed in this paper is to think of the estimates from Husby et al. (2014) as an upper bound for this effect. By specifying the function as a triangular distribution, we capture the uncertainty around the distribution of the marginal effect of protection on population growth. Hence, the usage of the triangular distribution in this paper is similar to that in the specification of the climate damage function, for example in the Integrated Assessment Model PAGE. In the event where a flood occurs in a region or when a dike is constructed, growth according to the SSP data is adjusted with a draw from the triangular distribution from the time period 'Event'. In the years following the event, the SSP data is adjusted with a draw from the triangular distribution of the appropriate time period. In addition to this stochastic approach to account for uncertainty, we provide a sensitivity analysis (see Supplementary Material C) in which we analyse the change in ED resulting from population change in the case where the estimates in Table 1 are twice as large, or twice as small. We run this sensitivity analysis for the regions in three distinctly different countries: the Netherlands, where government protection is high; Bulgaria, where government protection is low; and Italy, where some regions have high and others have low government protection against flooding.

2.4. *Behaviour scenarios*

To quantify the effects of the safe development paradox, we run the model for scenarios that exclude or include the population dynamics resulting from dike construction or flood events (*SFDpop*). By doing so, we can compare the common approach of flood risk assessment studies to a more realistic approach where population effects are taken into account. Furthermore, we assume as the baseline that households are boundedly rational (*BouRaHH*), so that they underestimate and overestimate risk, and that governments act reactively (*ReaGov*). We compare this scenario to a scenario in which governments are proactive (*ProGov*), as envisioned by the EU Floods Directive. Moreover, we analyse how mandatory building codes (i.e. elevation of new buildings considering its cost-efficiency) reduce the effect of the safe development paradox. Also, to analyse a shift towards not only a proactive government, but also towards policies that steer households towards rational behaviour, we include a scenario where households behave rationally (*RaHH*). This can be achieved by providing financial incentives that represent the uncertain outcome of the future, like the perceived risk reduction obtained from flood-proofing a home, with a more certain direct financial incentive, like a tax reduction or discount on an insurance premium, which reflects the reduced objective risk by flood-proofing a home. If designed well, such policies steer behaviour to become more rational, which is modelled here by assuming $\beta = 1$. The various combinations of behavioural scenarios described in this section are summarized in Table 2.

3. Results

3.1. *Reducing flood risk*

Fig. 2 shows the flood risk, expressed in EAD, after the adaptation by governments and residents of four different scenarios for the EU. To highlight changes when including or excluding the safe development population changes (SFDpop), we exclude here the building codes scenario and the steering of households towards rational behaviour (*RaHH*).The results show that flood risk is only marginally influenced by including or excluding *SFDpop*, despite the increase in exposed value caused by population growth (see Supplementary Material D). As the EAD is determined from the integral over the ED of flood events with

Table 1
Percentage point change in population growth as a result of an event, which is either a flood event or the construction of dikes (empirical estimates from Husby et al., 2014, upper and lower bound determined by a triangular distribution).

Time period (year)	Flood Estimate (Δ %)	Upper bound (Δ %)	Lower bound (Δ %)	Protection Estimate (Δ %)	Upper bound (Δ %)	Lower bound (Δ %)
Event	-0.00747	−0.00061	−0.01433	-0.00262	0.002675	−0.00792
Event + 1	0.000999	0.004739	−0.00274	0.006459	0.012588	0.00033
Event + 2	0.003199	0.007978	−0.00158	0.008387	0.014519	0.002254
Event + 3	0.001904	0.007296	−0.00349	0.005651	0.013791	−0.00249
Event + 4	-0.00219	0.001913	−0.00628	0.00706	0.013161	0.000959
Event + 5	-0.00532	−0.00074	−0.00991	0.008815	0.015149	0.00248
Event + 6	-0.00075	0.00494	-0.00644	0.010022	0.017794	0.002251
Event + 7	-0.00084	0.005787	−0.00746	0.007403	0.013531	0.001275
Event + 8	-0.00447	0.003985	−0.01293	0.010347	0.017717	0.002977
Event + 9	-0.00358	0.001532	−0.00869	0.009942	0.017097	0.002788
Event + 10	−0.00388	−4.22E-05	−0.00771	0.008795	0.015393	0.002196
Event + 11	−0.0014	0.005167	−0.00796	0.009364	0.014929	0.003798
Event + 12	0.000696	0.009225	−0.00783	0.006491	0.011528	0.001455
Event + 13	0.004223	0.010531	−0.00208	0.0042	0.008513	−0.00011
Event + 14	0.000918	0.006702	−0.00487	0.007572	0.013313	0.001832
Event + 15	0.003611	0.012444	−0.00522	0.003245	0.00835	−0.00186
Event + >y15	0.001718	0.004261	−0.00083	0.006094	0.00768	0.004507

different return periods, events with more frequent return periods (i.e. high probabilities) have a strong influence on the EAD, and those with less frequent return periods (i.e. low probabilities) count very little towards the EAD. Even in the reactive scenarios, over 50% of the regions offer a protection standard of 50 years or more, and therefore any increase in exposed value will cause only a minor change in EAD. The results thus show that including *SFDpop* does not significantly change previous conclusions regarding the EAD (Haer et al., 2019); proactive behaviour by governments leads to a significant reduction in EAD compared to reactive behaviour. When EU governments act proactively, the EAD to residential buildings is approximately 4.5 billion euro in 2050. In contrast, the EAD rises to approximately 10 billion when EU governments remain reactive. While this establishes the economic benefit of proactive behaviour, a potentially increased impact of extreme events due to the safe development paradox is not clearly visible when analysing the EAD, which is a yearly average. Therefore, in Section 3.2 we investigate the ED, which is an absolute value that denotes the consequences of flooding, for three extreme flood return periods.

3.2. *Increasing flood impact*

3.2.1. *Increased impact due to changing population growth*

Fig. 3 shows how including *SFDpop* influences the ED in 2050 for three extreme flood return periods: 100 years, 500 years and 1000 years. The top panels (A − C) show the difference in ED for the scenarios in which governments act reactively and where we include or exclude the safe development effects on population growth ($ED_{ReaGov+BouRaHH+SFDpop} - ED_{ReaGov+BouRaHH}$). In the reactive scenario, dike heights often remain at the same level as they are initialized in 2010 and flood events can still be considered infrequent. Therefore, the difference in ED between the two reactive scenarios that include or exclude *SFDpop* is relatively small. We find that when including *SFDpop* there is a mean increase of 58000 164000 and 183000 euro/km^2 for the 100-year, 500-year and 1000-year return period floods, respectively, in the reactive scenarios. However, these results are skewed upwards by some regions with a high exposed value. When comparing the median values, we find a relatively small increase of 15000 42000 and 45000 euro/km^2 for the 100-year, 500-year and 1000-year return period floods, respectively.

The lower panels (D − F) of Fig. 3 show the difference in ED for the scenarios in which governments act proactively, and in which we include ($ED_{ProGov+BouRaHH+SFDpop}$) and exclude ($ED_{ProGov+BouRaHH}$) the influences of government protection and flood events on population growth. In contrast to the reactive scenario, when governments act proactively the protection standards are frequently raised. As a consequence of doing so, and of the related population growth in the *SFDpop* scenario, there is a stronger increase in exposed value in the proactive scenarios than in the reactive scenarios. Now the results show that there is an average increase of 99000 530000 and 925000 euro/km^2 and a median increase of 16000 142000 and 240000 euro/km^2 for the 100-year, 500-year and 1000 year return period floods, respectively.

When aggregating the ED of all regions in the EU, we find that including *SFDpop* in the reactive scenario increases the ED by approximately 4 billion, 12 billion and 14 billion euro for the 100-year, 500-year and 1000-year return periods, respectively. Including *SFDpop* in the proactive scenarios leads to an aggregated increase of

Table 2
Behaviour scenarios and summary of the behaviour of governments and households for each scenario.

Scenario ID	Description
ReaGov + BouRaHH	Reactive governments and boundedly rational households
ProGov + BouRaHH	Proactive governments and boundedly rational households
ReaGov + BouRaHH + SFDpop	Reactive governments and boundedly rational households Population growth is influenced by protection and flood events
ProGov + BouRaHH + SFDpop	Proactive governments and boundedly rational households Population growth is influenced by increased protection or flood events
ProGov + BouRaHH + SFDpop + buildingcodes	Proactive governments and boundedly rational households Population growth is influenced by increased protection or flood events. New buildings are elevated.
ProGov + RaHH + SFDpop	Proactive governments and rational households Population growth is influenced by increased protection or flood events

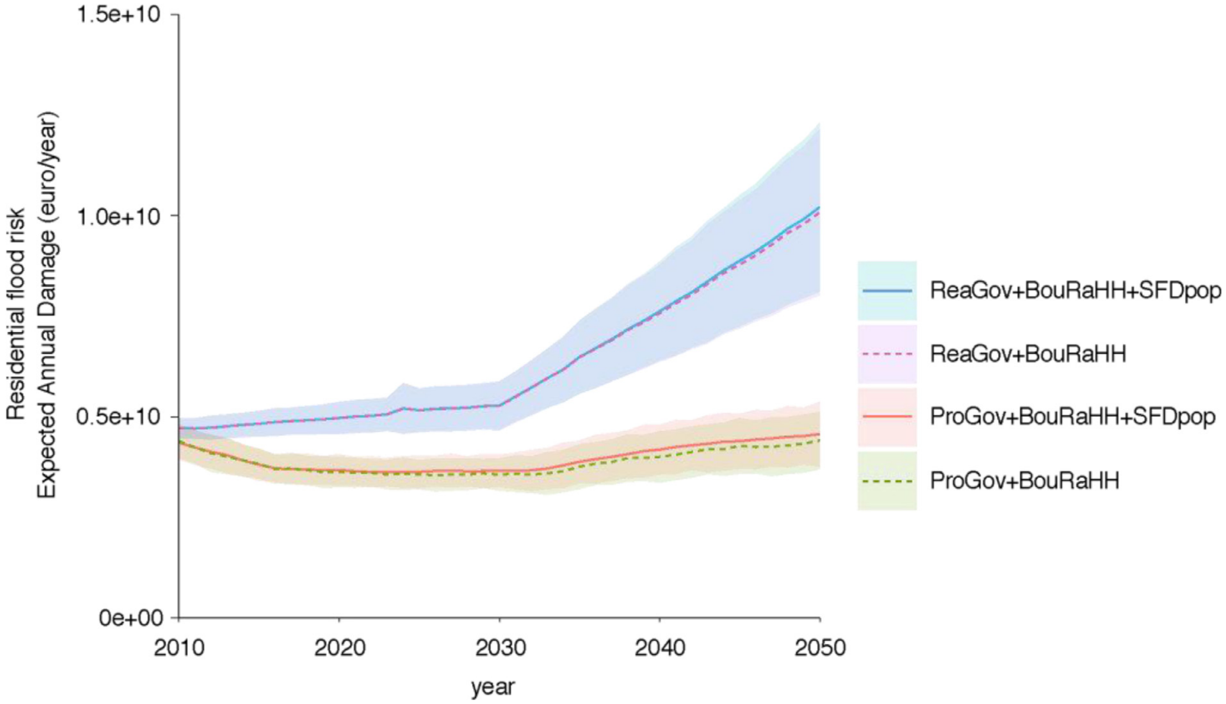

Fig. 2. Flood risk to residential buildings, expressed in EAD, for the period 2010 – 2050 for the RCP8.5 – SSP5 scenario. The results are shown for proactive and reactive governments, both including and excluding the influences of increased protection and flood events on population growth. Uncertainty bounds are based on 50 repetitions.

approximately 3 billion, 38 billion and 67 billion euro for the 100-year, 500-year and 1000-year return periods, respectively. Note that these high numbers do *not* represent single-event damage, as low probability events will not occur simultaneously throughout the EU. In reality, floods with these return periods have a very low probability of coinciding, and yearly damages are substantially lower, as shown by the EAD in Section 3.1. However, the values do provide an indication of the significance of accounting for the influence of dike construction and flood events on population growth in flood impact studies. For the RCP2.6 – SSP1 conditions we find a similar pattern with lower values: an increase of between 3 – 9 billion euro across return periods for the reactive government scenarios, and between 3 – 39 billion euro for the proactive government scenarios (Supplementary Material B). In Sections 3.2.2 and 3.3 we include the *SFDpop* in all scenarios.

We performed both the Kolmogorov-smirnov test and a Mann–Whitney *U* test to test if the distributions are different in mean, variability, and shape. The analysis (Supplementary Material E) shows that the distributions are significantly different ($p \leq 0.001$). Only the Mann–Whitney *U* for the 1000-year return period between ProGov_BouRaHH_SFDpop and ReaGov_BouRaHH_SFDpop does not show significant differences. However, as the Kolmogorov-smirnov test does return low p value ($p \leq 0.001$), we can still conclude that they vary in median, variability or shape.

3.2.2. Increased impact due to proactive instead of reactive government strategies

Besides the influence of dike construction and flood events on the population, well-intended proactive policy strategies can also potentially increase the impact of extreme flooding events, as households are less likely to protect themselves if they are protected by large engineering structures. Fig. 4 compares the ED for proactive ($ED_{ProGov+BouRaHH+SFDpop}$) and reactive ($ED_{ReaGov+BouRaHH+SFDpop}$) government strategies for the different return periods. Indeed, the results show an increase in ED for all return periods when governments act proactively (i.e. implement higher protection standards) instead of reactively.

In absolute terms, the ED increases on average by approximately 151000 715000 and 1203000 euro/km^2 and a median of approximately 23000 187000 268000 euro/km^2 for the 100-year, 500-year and 1000-year return periods, respectively if governments act proactively instead of reactively. In relative terms, the average values translate into an increase of between 4.4 and 8.6%, and the median translates into an increase of between 4.4 and 5.9% for the 100-year return period to the 1000-year return period. However, a quarter of the regions exhibit a relative median increase of 10% or higher across return periods, and between 2 – 5% of the regions even show a relative increase in ED of 30% or higher, with some regions showing a twofold increase in ED. The aggregated values for all regions in the EU further highlight the effect of the safe development paradox, as the ED increases by approximately 4 billion, 53 billion and 84 billion euro for the 100-year, 500-year and 1000-year return periods, respectively. For the RCP2.6 – SSP1 scenario we estimate an increase of approximately 4 billion, 28 billion and 40 billion euro for the 100-year, 500-year and 1000-year return periods, respectively (Supplementary Material B). We performed both the Kolmogorov-smirnov test and a Mann–Whitney *U* test to test if the distributions are different in mean, variability, and shape. The analysis (Supplementary Material E) shows that the distributions are significantly different ($p \leq 0.001$).

Fig. 4 highlights the geospatial distribution of the results. As can be expected, the greatest effect on ED in absolute numbers can be seen in areas with high levels of exposure, such as in large metropolitan areas. A proactive course generally leads to high protection standards in cities, thus excluding them from the comparison of impacts for return periods below 1000 years. However, when a disaster strikes (i.e. a flood with a 1000-year return period), our results show that moving from a reactive to a proactive government strategy leads to an increase in ED of 3 million euro/km^2 for the NUTS 3 area around Berlin, 5 million euro/km^2 for Rome, 6 million euro/km^2 for Prague, 17 million euro/km^2 for Paris and Brussels, and 22 million euro/km^2 for London in the year 2050. In relative terms the impact is more equally spread, with most of England, Ireland, France, Belgium and the Czech Republic showing an increase of 7% or more in ED. The same is true for central Italy, eastern

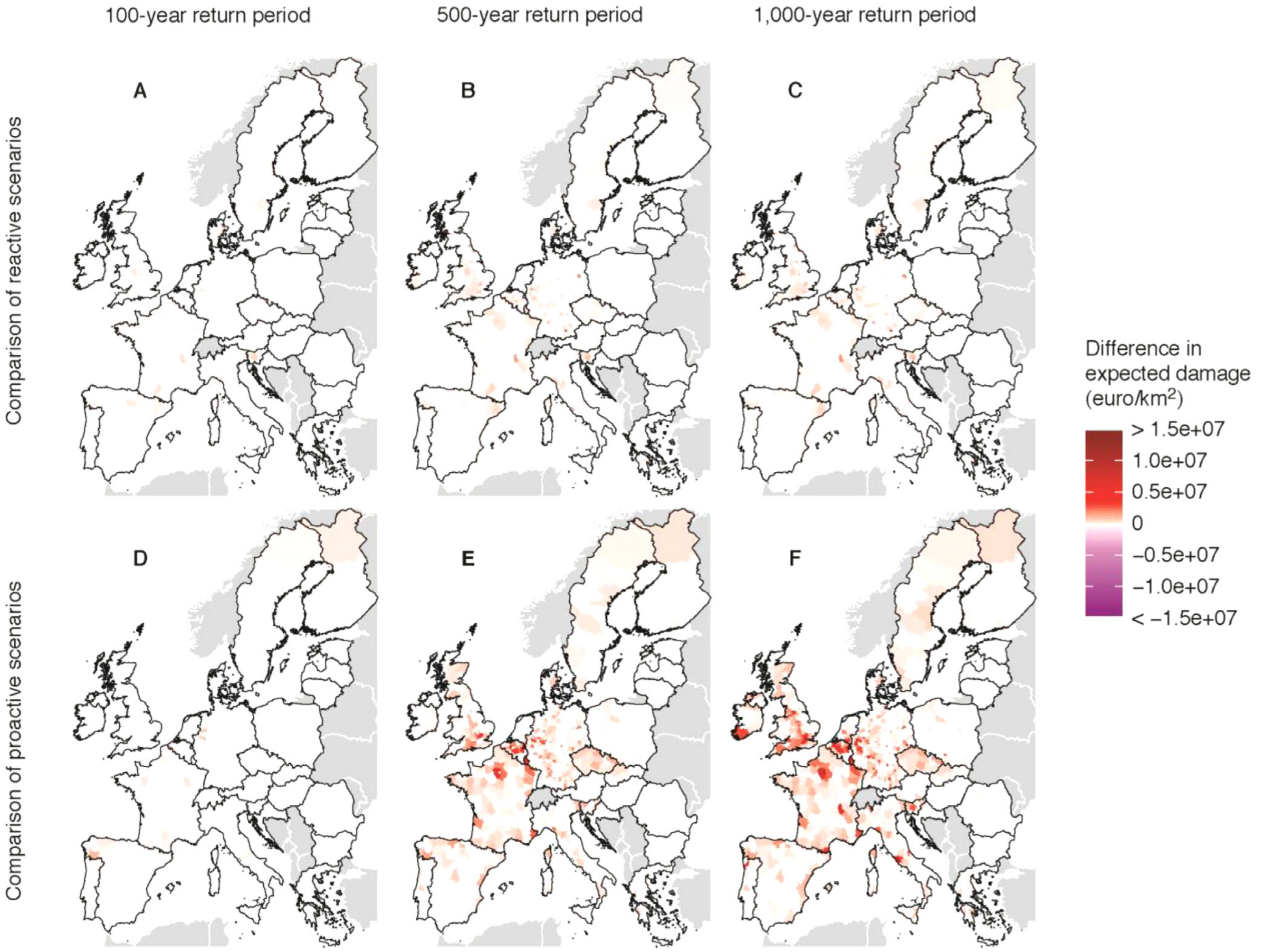

Fig. 3. The average difference in ED in euro/km^2 in 2050 under RCP8.5 – SSP5 conditions when including and excluding SFDpop. **A – C**: Difference between the scenarios in which the government acts reactively ($ED_{ReaGov + BouRaHH + SFDpop} - ED_{ReaGov + BouRaHH}$) for the 100-, 500-, and 1000-year return periods, respectively. **D – F**: Difference between the scenarios in which the government acts proactively ($ED_{ProGov + BouRaHH + SFDpop} - ED_{ProGov + BouRaHH}$) for the 100-, 500-, and 1000-year return periods, respectively. ED values are set to zero if the protection standards in a scenario are higher than the return period.

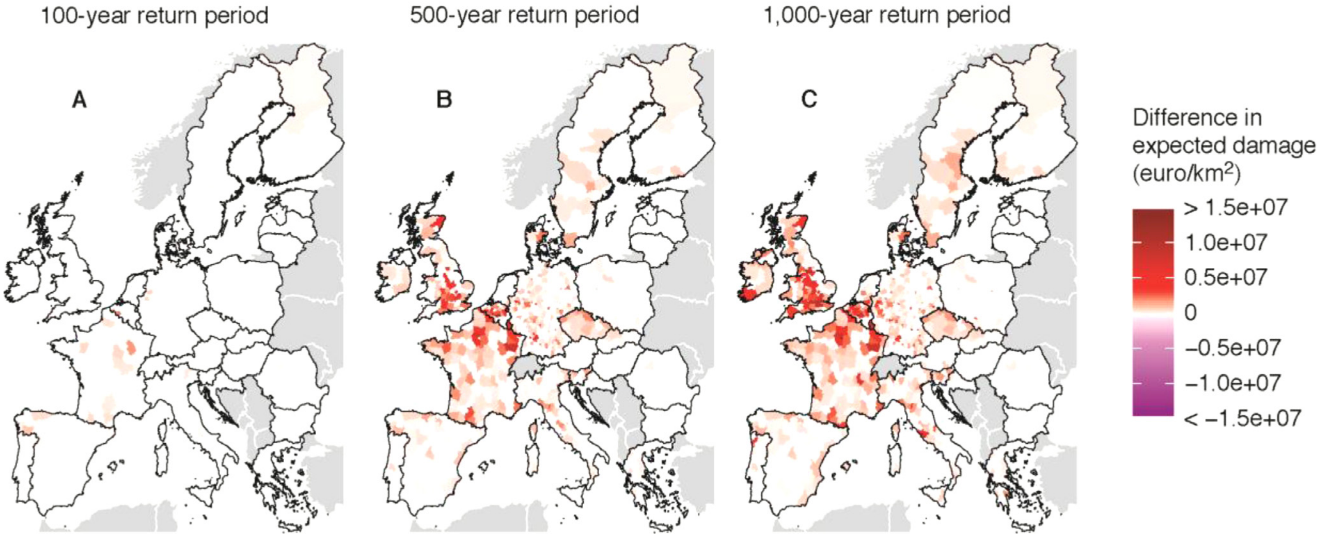

Fig. 4. The average difference in ED in euro/km^2 in 2050 under RCP8.5 – SSP5 conditions when comparing the proactive and reactive scenarios with boundedly rational households, including *SFDpop* (Difference = $ED_{ProGov + BouRaHH + SFDpop} - ED_{ReaGov + BouRaHH + SFDpop}$). **A**: 100-year return period. **B**: 500-year return period. **C**: 1000-year return period. ED values are set to zero if the protection standards in a scenario are higher than the return period.

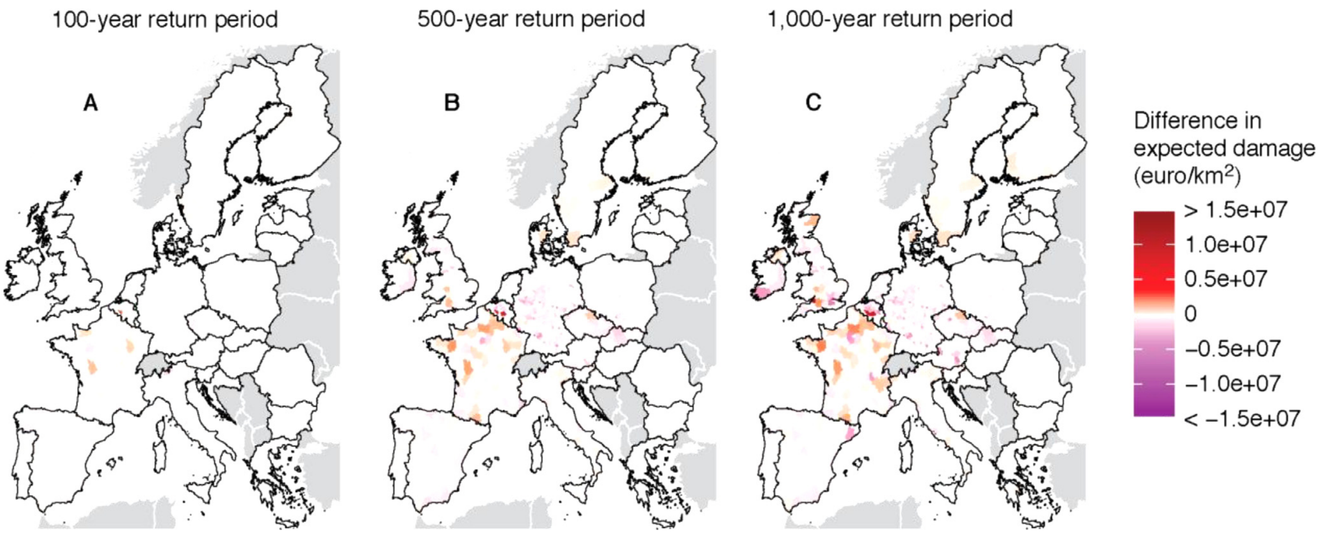

Fig. 5. The average difference in ED in euro/km^2 in 2050 under RCP8.5-SSP5 conditions when comparing the proactive government scenario where new buildings are elevated mandatorily through building codes versus a reactive government scenario without building codes. In both cases, households are boundedly rational (Difference = $ED_{ProGov + BouRaHH + SFDpop + buildingcodes} - ED_{ReaGov + BouRaHH + SFDpop}$). **A**: 100-year return period. **B**: 500-year return period. **C**: 1000-year return period. ED values are set to zero if the protection standards in a scenario are higher than the return period.

Spain and southern Scandinavia.

The main driver behind this increase in ED when governments act proactively lies in the decrease in protective measures taken by residents. When analysing the share of residential areas protected by flood-proofing or elevating, we find a mean of 39% across regions for the reactive scenario and a mean of 36% for the proactive scenario, which in relative terms is an 8% decrease. Moreover, if we analyse the regions in the lowest quartile of share of protected buildings, we find that in the reactive scenario 16% of the residential buildings are protected by flood-proofing or elevating, while in the proactive scenario this falls to 11%. In relative terms this is a decrease of 31%. While increased protection standards in the proactive scenario lead to a significant decrease in flood risk (EAD), they also lead to a decrease in protective efforts made by households, and consequently an increase in the impact of extreme events (ED).

3.3. Measures to counter the safe development paradox

3.3.1. Mandatory risk reduction: Building codes

Governments can actively counteract the safe development paradox. One frequently applied policy is to implement mandatory building codes, which forces new development to implement loss-reducing measures. Fig. 5 shows how the ED changes if the government becomes proactive, but also implements building codes in the form of mandatory elevation, which is the most cost-effective measure for new buildings. Compared to the results shown in Fig. 4, the difference in ED between the proactive and reactive government strategies becomes significantly lower.

When implementing mandatory elevation, the average reduction in ED amounts to 31000, 372000 and 543000 euro/km^2 and a median reduction of 3000, 82000 and 103000 euro/km^2 for the 100-, 500-, and 1000-year return periods, respectively. In relative terms we see a median reduction of -1.8%, 1.8% and 1.6% across the analysed regions for the 100-year, 500-year and 1000-year return periods, respectively. Note that the increase found for the 100-year return period is lower than the increase of 4.4% found in Section 3.2.2. We find an aggregated change of 10 million, 323 million and 532 million euro for the 100-year, 500-year and 1000-year return periods, respectively. These findings show the significant gain achieved by steering adaptive behaviour towards the implementation of building-level measures. The statistical analysis (Supplementary Material E) shows that the distributions are significantly different ($p \leq 0.001$). Only the Mann–Whitney U for the 1000-year return period between ProGov_BouRaHH_SFDpop and ProGov_BouRaHH_SFDpop does not show significant differences. However, as the Kolmogorov-smirnov test does return low p value ($p \leq 0.001$), we can still conclude that they vary in median, variability or shape.

3.3.2. Voluntary risk reduction: incentives to act rationally

Governments can also counteract safe development by stimulating voluntary risk reduction, for instance through tax reductions, subsidies or awareness campaigns. Furthermore, insurance companies could offer discounts on insurance premiums if households decide to implement loss-reducing measures. Effectively, these measures stimulate more rational behaviour of residents, as modelled here in the *RaHH* scenario. For both the 100-year and 500-year return periods, the proactive strategy in which households act rationally leads to a reduction in ED in all examined regions. For the 1000-year return period, most regions show a reduction in ED, and the regions with an increased ED still have a lower ED than they would have had if governments acted proactively and households behaved rationally (Fig. 6). Regions in north-western and central Europe, which face frequent flooding and generally have greater exposed value, show a larger reduction in ED.

When households exhibit rational behaviour, the average reduction in ED amounts to 511000 1835000 and 1503000 euro/km^2 and a median reduction of 147000 440000 and 343000 euro/km^2 for the 100-year, 500-year and 1000-year return periods, respectively. Note that the 1000-year return period yields a lower average reduction, as some regions that were excluded from the 500-year return period (i.e. regions where protection standards are $> =$ 500 years) are included in the 1000-year return period analysis. In relative terms we find a median reduction of 21%, 14% and 9% across the analysed regions and an aggregated change of 13 billion, 96 billion and 88 billion euro for the 100-year, 500-year and 1000-year return periods, respectively. For the RCP2.6 − SSP1 scenario we estimate a reduction of approximately 14 billion, 52 billion and 53 billion euro for the 100-year, 500-year and 1000-year return periods, respectively (Supplementary Material B). These values indicate the significant gains achieved from steering adaptive behaviour towards the increased implementation of building-level measures. The statistical analysis (Supplementary Material E) shows that the distributions are significantly different ($p \leq 0.001$).

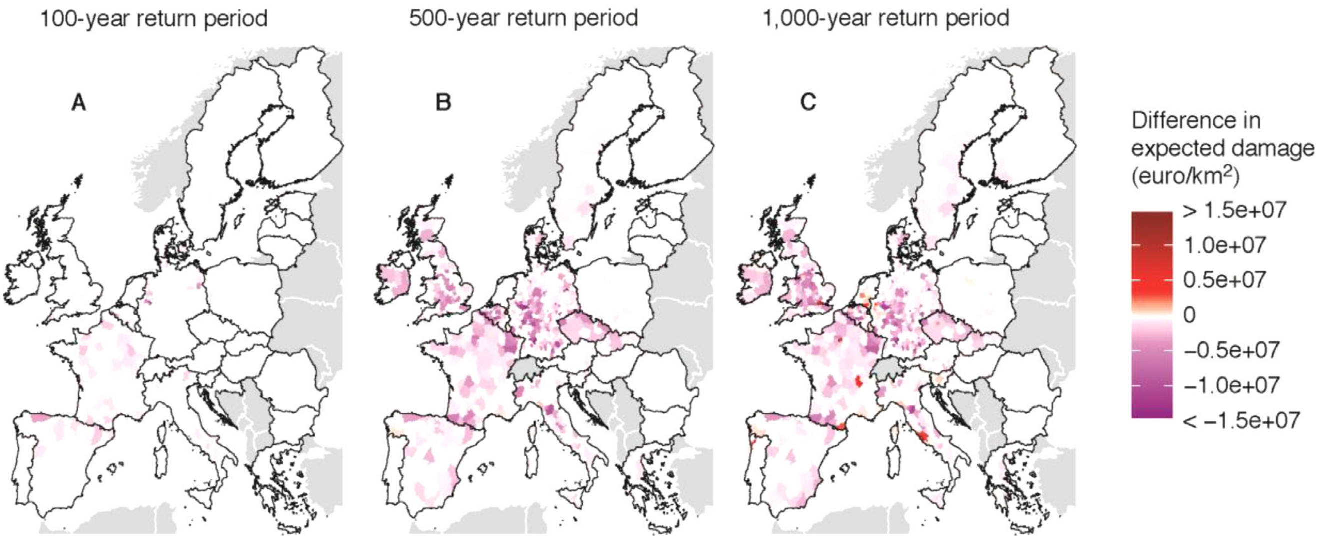

Fig. 6. The average difference in ED in euro/km^2 in 2050 under RCP8.5 – SSP5 conditions when comparing the proactive scenario in which households act rationally, and the reactive scenarios in which households act boundedly rationally, which both include *SFDpop* (Difference = $ED_{ProGov+RaHH+SFDpop} - ED_{ReaGov+BouRaHH+SFDpop}$). **A**: 100-year return period. **B**: 500-year return period. **C**: 1000-year return period. ED values are set to zero if the protection standards in a scenario are higher than the return period.

4. Discussion

4.1. Safe development parameters

While this study provides key insights into the quantitative impacts of the safe development paradox, the scope is limited to the economic damage caused by extreme events. However, the consequences of the safe development paradox potentially extend further. Our model includes a mechanism of population response by which the population in a flood-prone region increases as a result of increased protection, in line with the results of Collenteur et al. (2015), Husby et al. (2014) and Burby (2006). As we show in Supplementary Material D, the population in flood-prone areas increases significantly over the years when governments act proactively. This leads to the prediction of roughly 76 million people living in flood-prone areas in 2050, compared to 66 million people in the baseline SSP scenario. Even when governments act reactively, there are 1 million more people living in flood-prone areas compared to the baseline. This increase in population is a proximate warning for the potential increase in loss of life if a disaster strikes, which is an important input in models used for determining optimal flood protection levels (Jonkman and Vrijling, 2008). Furthermore, although we capture dynamics relevant to the safe development paradox by altering the SSP projection in flood-prone areas, the use of SSPs still represents a static assumption regarding changes in demography. However, flood events and climate change in general can have non-linear effects on the displacement of people (López-Carr et al., 2014; Penning-Rowsell et al., 2013), migration flows (Gray and Wise, 2016; Pasini and Amendola, 2019) and climate-induced resettlement (López-Carr et al., 2014; López-Carr and Marter-Kenyon, 2015). While this lies outside of the scope of this manuscript, capturing these complex dynamics in addition to safe development dynamics would improve future estimates of impact and risk.

Moreover, there are additional impacts to consider, such as enhanced societal disruption and the increase in indirect damages resulting from the safe development paradox. Koks et al. (2015) showed for the case study of an extreme event in Rotterdam Harbour that for low-probability extreme events, indirect losses can outweigh direct damages. Such indirect losses can be aggravated if, prior to a flood, economic activities in flood-prone areas grew after protection standards were increased. This effect might also cause indirect damage in unaffected regions if an extreme event causes damage to critical infrastructure (Koks et al., 2015). Further research should therefore combine the analysis of direct damages as shown here with analysis of the indirect impact of extreme events (Giesecke et al., 2012). Moreover, in the aftermath of Hurricane Katrina, which is an example of the safe development paradox (Baldassarre et al., 2015), it was shown that lower income groups were affected more than higher income groups (Kates et al., 2006; Masozera et al., 2007). This emphasises that social injustice cannot be ignored when designing policies to reduce the effects of the safe development paradox. While out of the scope of this research, ABMs could be designed to capture the complex processes of urbanization, and could subsequently be utilized to capture social segregation effects related to the safe development paradox. Moreover, this study does not explicitly capture income variability and budget constraints. As shown by (Hudson et al. 2019), for instance, the affordability of certain adaptation strategies could influence the uptake of the measure. In this study it would have resulted in a reduced uptake of measures for all scenarios, leading to higher EAD and ED, while the main conclusions would remain the same. However, future work could benefit from the inclusion of budget constraints to further improve the accuracy of the estimates.

In this study we use the only empirical data available on the effects of flood occurrence and levee construction on population growth Husby et al., 2014). However, as this data was specifically obtained for the Netherlands, uncertainties are involved when applying it to different regions. Nevertheless, our sensitivity analysis (see Supplementary Material C) indicates that assuming the effect is twice as large or twice as small has a minor influence on the overall ED results. When the effect on population growth is twice as small, the effect on the ED is on average 2.62% smaller. When the effect on population growth is twice as large, the effect on the ED is on average 6.12% larger. However, the sensitivity analysis also shows that, under certain circumstances, for individual regions the percentage population change with respect to the baseline can be larger. This is not only a result of the sensitivity, but can also result from (1) the stochastic occurrence of flood events, (2) the timing of increased government protection, and (3) the stochastic draw from the triangular distribution for each event and each subsequent year. Therefore, further research should focus on obtaining a wider range of data on the effect of the safe development paradox on population growth for different regions. This will enabled a more detailed and robust analysis to be obtained on a smaller scale.

Finally, it is important to realize that the results on the safe development paradox presented here are based on scenarios where all governments are either reactive or proactive, and all households are either boundedly rational or rational. In reality, there will most likely be a gradual shift towards proactive governmental action in the EU, following the EU Floods Directive. Moreover, policies that steer household behaviour towards rational behaviour might not achieve this completely, and it will surely not be implemented at the same time nor in the same way in different EU member states. Alternatively, governments could apply other means which have less impact on the ED, such as the construction of reservoirs or the restriction of building in risk zones altogether. However, our results effectively provide an upper and lower bound of the effects of the safe development paradox for the EU, and signal the importance of developing policy measures to counteract the negative effects.

4.2. Policy implications

Our results confirm that the increasing protection provided by large engineering structures can cause an increased impact of extreme events due to greater exposure. This enhanced exposure results from population growth effects that follow increased protection or flood events, and thus increased vulnerability, as people neglect to take building-level measures. While the reduction of yearly average risk remains an important input variable for economic decision-making, our results show that careful consideration is needed of the negative side-effects of proactive policies. Frameworks such the EU Floods Directive (EU, 2007), the Sendai Framework for Disaster Risk Reduction (UN, 2015) and the Warsaw International Mechanism for Loss and Damage (UNFCCC, 2013) acknowledge and stimulate local measures that could reduce adverse effects, but not in the context of countering such effects of well-intended large-scale measures. Without explicitly incorporating policies against these adverse effects in adaptation strategies, extreme flood events will cause more damage and potentially lead to large-scale disruption of society.

To reduce the economic impacts of extreme events, governments or local authorities could stimulate voluntary or mandatory building-level measures. Measures such as flood-proofing or elevating would reduce the economic damage caused by floods that overtop the design level of protection standards. While such measures are often economically rational to take (Aerts et al., 2014; Kreibich et al., 2011; Poussin et al., 2015), people are generally not inclined to implement them. An example can be seen in the Netherlands, where high protection standards lead to low awareness and few measures being implemented at the household level, while households situated outside the embankments often have elevated houses. Section 3.3.1 shows that such mandatory building codes, in this case elevation, indeed reduce the effects of the safe development paradox. Therefore, when choosing a proactive government strategy aimed at large-scale protection, policies need be aimed at stimulating the implementation of building-level measures to reduce the impact of extreme events that overtop the design levels of dikes and levees.

While governments are well positioned to stimulate such building-level measures through tax deduction, subsidies and building codes, the implementation of policy and regulation by governmental institutes is usually slow (Surminski et al., 2015). In contrast, market mechanisms can lead to swift changes in behaviour and might therefore be better positioned to stimulate household adaptation (Surminski et al., 2015). Previous studies suggest that the insurance sector could play a vital role in stimulating the implementation of loss-reducing measures (Botzen et al., 2009; Kunreuther, 1996). For instance, insurance against flood damage could be combined with an insurance premium discount if households install flood-proofing or elevate their houses. Botzen et al. (2009) show that households might be willing to adopt loss-reducing measures if they receive a premium discount, while Haer et al. (2016) prove that this could significantly contribute to reducing the impact of flood events. Section 3.3.2 shows how such measures that effectively aim to stimulate more rational household behaviour might be effective in counteracting the safe development paradox.

Moreover, our results show that a major role should be played by large metropolitan areas such as the NUTS 3 regions around Paris and Brussels. In relative terms these areas might be less subjected to the safe development paradox, but as a result of their high exposed value they are hit hardest in absolute terms. While government-led initiatives can force or stimulate cities to reduce their vulnerability to extreme events, cities themselves are increasingly becoming leaders in climate adaptation. For instance, initiatives like C40 Cities[2] and the Sustainable Cities Institute[3] are emerging, through which cities themselves take on the responsibility to reduce their vulnerability to climate change and associated impacts. In this study we indicate the importance of combining large-scale protective efforts with local-level or building-level measures. Considering their knowledge of the local situation, cities themselves can best determine where extreme events could impact, for instance, critical infrastructure, businesses, or social and cultural hotspots. As such, they can stimulate or implement tailor-made policies, regulations and measures that are appropriate for infrequent but highly disruptive events.

The solutions offered to limit the adverse effects of the safe development paradox are not only confined to building-level measures. Studies have shown that flood-prone regions experience significant development (Hallegatte et al., 2013), which in combination with increased public protection can lead to a significantly larger impact of extreme events, as shown in this study. Therefore, it should be carefully considered if new development is desirable in the face of flood risk and the safe development paradox, or if new development has to be regulated, for instance by mandatory flood-proofing, or even prohibited in certain high-risk areas (Stevens et al., 2010). Of course, this should also be carefully weighted, as the benefits of development in risk areas might be larger than the potential losses. Therefore, it is important to institutionalize flood awareness and flood adaptation strategies within local government planning, by forcing local governments to include adaptation planning in comprehensive development plans, for example (Burby, 2006).

5. Conclusion

In this study we analyse and quantify the consequences of the so-called safe development paradox for the EU, by using an ABM that integrates the adaptive behaviour of governments and households with a large-scale flood risk assessment. We adapt this model to better capture the change in population growth which can occur after a flood event, or after governments increase protection, as this in turn leads to higher exposed values. Thus, this study quantifies the economic impact of the safe development paradox on a continental scale, which results in three main conclusions.

First, based on our findings we can conclude that the change in population growth caused by the safe development paradox is an important addition to risk assessments, as it leads to higher exposure and higher damages. Depending on how governments act, which in our model can be reactively or proactively, including this effect on population growth leads, for the 500-year return period, to an increase in ED of between 12 and 38 billion euro under RCP8.5 − SSP5 conditions, and between 8 and 26 billion euro under RCP2.6 − SSP1 conditions. Note that this does not refer to single-event damage, but the aggregated increase in ED for extreme events summed for all regions in the EU.

Second, proactive government decision-making leads to lower yearly flood risk but higher impacts of extreme events, compared to a reactive approach, if no policies are in place to stimulate building-level

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[2] www.c40.org.www.c40.org.www.c40.org

[3] www.sustainablecitiesinstitute.org.www.sustainablecitiesinstitute.org.www.sustainablecitiesinstitute.org

protective efforts by households. In this case, the aggregated ED of floods with extreme return periods in the EU is estimated to increase by 53 billion euro for the 500-year return period under RCP8.5 – SSP5 conditions, and 28 billion euro under RCP2.6 – SSP1 conditions. While this should not be interpreted as single-event damage, it does signal the significant negative effect of proactive large-scale protection decisions by governments.

Third, based on our findings we conclude that steering household behaviour towards rational behaviour (i.e. no underestimation or overestimation of risk) leads to greater implementation of building-level measures, which counteracts the negative effects of proactive government action. We do not go into depth on the exact type of steering mechanisms that should be used, but this could be a discount on an insurance policy if a household implements risk-reducing measures, for example. When households are steered towards fully rational behaviour, the aggregated ED is actually lowered across return periods. For instance, for the 500-year return period, ED is 96 billion euro lower under RCP8.5 – SSP5 conditions, and 52 billion euro lower under RCP2.6 – SSP1 conditions, despite the proactive instalment of large-scale protection by governments.

This research provides the first quantification of the economic effects of the safe development paradox. However, we also highlight aspects that should be addressed by further research, such as the effects on loss of life, business interruptions, and impacts on critical infrastructure. Further research could also focus on developing detailed regional data that can feed into the large-scale model, and acquiring detailed empirical data on behavioural aspects, which could help to improve estimates for household behaviour.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.gloenvcha.2019.102009.

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