Flood Insurance Arrangements in the European Union for Future Flood Risk under Climate and Socioeconomic Change

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Abstract

Flood risk will increase in many areas around the world due to climate change and increase in economic exposure. This implies that adequate flood insurance schemes are needed to adapt to increasing flood risk and to minimise welfare losses for households in flood-prone areas. Flood insurance markets may need reform to offer sufficient and affordable financial protection and incentives for risk reduction. Here, we present the results of a study that aims to evaluate the ability of flood insurance arrangements in Europe to cope with trends in flood risk, using criteria that encompass common elements of the policy debate on flood insurance reform. We show that the average risk-based flood insurance premium could double between 2015 and 2055 in the absence of more risk reduction by households exposed to flooding. We show that part of the expected future increase in flood risk could be limited by flood insurance mechanisms that better incentivise risk reduction by policyholders, which lowers vulnerability. The affordability of flood insurance can be improved by introducing the key features of public-private partnerships (PPPs), which include public reinsurance, limited premium cross-subsidisation between low- and high-risk households, and incentives for policyholder-level risk reduction. These findings were evaluated in a comprehensive sensitivity analysis and support ongoing reforms in Europe and abroad that move towards risk-based premiums and link insurance with risk reduction, strengthen purchase requirements, and engage in multi-stakeholder partnerships.

Keywords: climate change adaptation; flood risk; insurance; public-private partnerships; risk reduction.

1. Introduction

Flooding has been considered the natural hazard with the largest impact on society (CRED-UNISDR, 2015). Moreover, future flood risk will increase due to changes in flood hazards (flood frequency and intensity), exposure (values at risk), and vulnerability (the susceptibility to losses). The increase in flood risk due to socioeconomic development and climate change (IPCC, 2018) has placed growing pressure on insurance markets (Mechler et al., 2014; European Commission, 2017a; Cremades et al., 2018). This has resulted in declining welfare for those in flood-prone areas, for example, due to rising insurance premiums or uncertainty over future insurance coverage as risks become perceived as less insurable. Moreover, the increasing flood risk has initiated discussions about insurance market reforms (Michel-Kerjan and Kunreuther, 2011; European Commission, 2013; Surminski et al., 2015). For instance, in the United States, it is being debated whether flood risk can be privately insured (Michel-Kerjan et al., 2015; Kousky et al., 2018) and which insurance mechanisms can provide better incentives for policyholder risk reduction (Kunreuther, 2015b; Kousky et al., 2018). Such incentives are important because policyholders can lower potential flood impacts (Hudson et al., 2016; Surminski et al., 2016; Aerts et al., 2018), for instance, by floodproofing buildings. Floodproofing consists of property-level measures which, for example, limit the potential damage once water has entered a building (known as wet floodproofing) or attempt to prevent water from entering a building (known as dry flood-proofing).

Flood insurance reform is also being debated in Europe, where each country has developed particular insurance arrangements as a result of different risk profiles and public policy preferences (Surminski, 2017). One feature of the discussion about flood insurance reforms is the desirability of replacing fixed-rate insurance premiums with risk-based premiums (European Commission, 2013). Risk-based premiums may, in theory, incentivise damage mitigation by rewarding those who reduce risk with premium discounts (Lamond and Penning-Rowsell, 2014). The aggregated effects of individual action could provide a noticeable contribution to overall risk reduction, in turn lowering pressure on insurance markets. However, a disadvantage of risk-based premiums is that they may be unaffordable for low-income households in high-risk areas (DEFRA, 2011; Hudson et al., 2016; FEMA, 2018; Hudson, 2018). Debates about flood insurance reforms have also focussed on the desirability of different degrees of government and private sector involvement and whether coverage should be mandated or voluntary.

The main objective of this paper is to conduct a comparative analysis of a range of flood insurance market structures across Europe in relation to changing flood risk to identify common patterns of desirable characteristics of different types of flood insurance arrangements. This can provide a starting point for future flood insurance market reforms across Europe. For this investigation, we couple pre-existing models of insurance sectors, consumer behaviour, and flood risk in a single model evaluation framework, called the Dynamic Integrated Flood and Insurance (DIFI) model, so that a holistic assessment can take place. Such an analysis should account for the risk management objectives of countries because the development of disaster insurance occurs in response to public policy choices based on these objectives (Surminski, 2017). The DIFI model evaluation is conducted from the perspective of policymakers who wish to promote disaster insurance markets that manage the trade-offs between important insurance market outcomes. To account for these trade-offs, we conduct a multi-criteria analysis (MCA) of the key evaluation criteria, where the weights associated with each criterion act as a proxy for the risk management objective. Our research directions are extensions of the previous literature, which has focussed on qualitative evaluations of flood insurance markets (Michel-Kerjan and Kunreuther, 2011) or evaluations of a single market structure (Hudson et al., 2016). Due to limited information on household-level risk perception and mitigation efforts at the European scale, we employ a stylised scenario approach in a unified modelling framework, for which we perform an extensive sensitivity analysis. Moreover, an established modular model framework can act as a basis for future research as the DIFI model can be updated when new information becomes available, such as on flood risk or property-level behaviour. Our evaluation of stylised flood insurance arrangements allows for drawing generalisable lessons which are also applicable outside of Europe.

2. Methods

An evaluation of flood insurance market structures suitable for policymakers requires an analysis of economic efficiency and equity of different market features. We define efficiency as incentives for risk reduction that originate from the ability of insurance to send a price signal of risk (Baur, 2016). Moreover, low premium costs for households can lead to higher coverage levels, as noted in Lamond and Penning-Rowsell (2014). Whilst there is no universal definition of equity (Thaler and Hartmann, 2016), we focus on its distributive aspects by recognising that those threatened by flooding should have equal opportunities to purchase flood insurance and that risk-spreading mechanisms, like insurance, include principles of solidarity (Johnson et al., 2007; Thaler and Hartmann, 2016; Sayers et al., 2018; Thaler et al., 2018). Therefore, equity is taken to mean the affordability of premiums and the degree of risk sharing amongst households facing high and low flood risk.

We employ the DIFI model to assess the criteria listed in Table 1 for two time periods (2015–2035 and 2035–2055) to conduct a holistic evaluation of the range of different flood insurance market structures for a country. We design six categories of stylised market structures, which capture the core market features that influence the evaluation criteria, to evaluate existing structures in European countries and the benefits of market reform—for example, the drivers of insurance purchase (e.g., voluntary or mandated) or the differentiation of insurance premiums according to risk.

Our evaluation criteria are based on the debate surrounding flood insurance mechanisms as collected through a literature review (see SI8.1). This assessment highlights the importance of the following desirable characteristics of flood insurance arrangements: 1) the overall insurance penetration rate, 2) incentivised risk mitigation, 3) the ability to absorb large losses, 4) the ability to provide quick and certain compensation, and 5) the affordability and availability of insurance. These characteristics are further operationalised in our study according to the criteria in Table 1, which have been derived as follows. Criteria 1 and 2 are the aforementioned benefits of higher penetration rates and risk mitigation efforts by households. The Solvency II European Union legislation requires the compliance of European insurers to an annual insolvency probability of 0.5 per cent. Therefore, insurers are already regulated to be able to absorb a large loss, which implies that characteristic 3 is met and does not need to be included as a separate criterion in our study. Similarly, characteristic 4 is met as this study focusses on formal flood insurance arrangements which provide quick and certain compensation. Characteristic 5 is further refined into costs imposed on low-risk households (criteria 3) and unaffordability of insurance for high-risk households (criteria 4) to capture the core equity concerns.

These criteria were drawn from literature regarding flood, and natural hazard, insurance (see SI8.1.1). This was complemented by a qualitative assessment of responses collected from a stakeholder engagement process (see SI8.1.2). The purpose of the stakeholder engagement process was to get a qualitative check of the MCA criteria and weighting derived from the literature review. However, whilst the stakeholder engagement confirmed that the selected criteria were suitable, the sample was not fully representative of all stakeholders or Europe as a whole. Nevertheless, since our MCA approach is based on the literature review, it does not strongly rely on the implications arising from the stakeholder consultation.

Our final four criteria in Table 1 closely match the criteria used by Hochrainer-Stigler and Lorant (2018) for an MCA of disaster risk management partnerships across Europe. Their selected criteria are economic efficiency (costs of insurance), risk reduction incentives, equity (solidarity and decreasing inequalities), and feasibility. Whilst Hochrainer-Stigler and Lorant (2018) derived these criteria from a different process, they strongly resemble our selections, which affords confidence in their suitability. Within our MCA framework, each of the four evaluation criteria in Table 1 are associated with a specific weight. Altering the size of the weights changes the relative importance of the evaluation criteria. As such, different weighting schemes represent different public policy objectives from national solidarity (a focus on affordability and market penetration rates) to insurance being a private matter (a focus on risk signalling). The relative importance attached to each of these criteria can change the outcomes of the analysis regarding the optimal market structure.

The DIFI modelling framework is presented in Figure 1 and explained in detail in the supplementary information (SI) section SI1. The model consists of several modules: flood risk assessment under climate and socioeconomic change (SI2), insurance sector (SI3), and consumer behaviour (SI4). Based on the flood risk assessment, the DIFI model calculates flood insurance premiums (SI3) using the premium setting rules developed in Paudel et al. (2015) and Paudel et al. (2013) and simulates consumer behaviour dependent on the flood insurance market structure (see SI4). Consumer decisions involve purchasing insurance and investing in flood damage mitigation measures, which is determined in a cost-benefit assessment that applies a subjective expected utility framework. Depending on the insurance market structure, incentives for risk mitigation resulting from premium discounts are included. The model was used to estimate the evaluation criteria in Table 1, which serve as input for the final evaluation framework (SI5). This evaluation is based on a comparative analysis to provide an indication of the relative benefits of the different insurance market structures, which are robust to some of the uncertainty in the model regarding the precise estimated criteria values. The criteria were estimated over two twenty-year periods: 2015–2035 and 2035–2055. The focus of the model is on those households at highest risk (i.e., those living in the area that can be affected by the one in one-hundred-year flood).

Table 1: Summary and definition of the evaluation criteria estimated by the DIFI model

	Definition	**Benefit/Cost**
Criterion 1: Insurance penetration rate	The average percentage of households with high flood risk that buy sufficient insurance at the national level	Benefit
Criterion 2: Incentivised risk reduction	The total net present value (NPV) of incentivised risk reduction conducted by households at the national level	Benefit
Criterion 3: Cost on low-risk households	The NPV of the subsidy of high-risk households paid by low-risk households, aggregated to the national level	Cost
Criterion 4: Unaffordability of insurance	The NPV of the magnitude of unaffordability, measured as the portion of premiums that cannot be paid from a poverty-adjusted disposable income at the national level	Cost

2.1. Flood risk modelling (SI2)

An existing coupled hydrological-flood-damage model (LISFLOOD) at the European scale estimates the current and future risk of riverine floods across Europe, as presented in Feyen et al. (2012) and Rojas et al. (2013).

The combined model estimates the household-level loss $[L(p)_{j,t}]$ from a flood with an exceedance probability (occurrence probability) of p in NUTS 2 region[1] j at time t given a certain level of flood protection (PS_j). $L(p)_{j,t}$ is an increasing function of hazard $[H(p)_{j,t}]$, exposure $(E_{j,t})$, and vulnerability $(V_{j,t})$, which is shared over households at risk $\left(N_{j,t}\right)$, as shown in eq. (1). Eq. (1) estimates the average flood damage per household from a given flood event. Kron (2005) provides definitions for exposure, vulnerability, and hazard: exposure is the value of assets that can be flooded, vulnerability is the degree to which assets are susceptible to being damaged, and hazard is defined as the magnitude of a hydrological event. The underlying flood risk model combines each of the above components using spatially referenced data to value the damage caused by a flood of a given exceedance probability. A

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[1] A NUTS 2 region is an European Union geo-spatial code based roughly on national administrative divisions. For instance, German NUTS 2 regions correspond to a *regierungsbezirke*, whilst French regions correspond to *région.* However, not all such regions are at risk of flooding. The population affected by flooding is also estimated through the risk model.

damage probability curve is fitted based on a power-law function[2] from several occurrence probabilities. Damage amounts for the following return periods are estimated as: 1/2, 1/5, 1/10, 1/20, 1/50, 1/100, 1/250, and 1/500. A Monte Carlo simulation using these return periods produces an estimate of the annual expected flood loss per household and the variance of losses.[3]

In estimating the annual expected flood loss per household, the presence of protection standards (i.e., dikes) is accounted for in the hazard element of the flood risk model. A country that lacks protection standards would calculate risk over the probability range [0, 1]. Following Jongman et al. (2014), the presence of protection standards truncates the upper bound from 1 to the flood probability that exceeds the protection standard (PS_j). For example, a protection standard of 1 per cent means that only a flood event with an exceedance probability equal to or smaller than 1 per cent will cause an impact. It is assumed that protection standards are fixed over time (Winsemius et al., 2016; Alfieri et al., 2018; Vousdoukas et al., 2018). This implies that government investments in flood protection infrastructure maintain a constant dike failure probability when river discharges alter as a result of climate change. The values of PS_j used are taken from Jongman et al. (2014), who provide an estimate of regional protection standards in Europe.

$$L(p)_{j,t} = \frac{f\left(H(p)_{j,t}, E_{j,t}, V_{j,t}\right)}{N_{j,t}} | PS_j \tag{1}$$

The output of the coupled hydrological-flood-damage model is converted into average annual expected losses for households in an area with a flood probability of at least 1 per cent in the absence of protection standards. This area is defined as having high flood risk, which is consistent with Schwarze and Wagner (2007) and FEMA (2016). Low-risk households are those with a flood occurrence probability below 1 per cent (in the absence of protection standards). Future flood risk is modelled by assuming that climate changes follow the SRES A1 scenario. Moreover, future exposed assets and population are estimated by rescaling flood impacts through the ratio of the future and baseline real GDP[4] or population according to the ensemble mean of the various shared socioeconomic pathway (SSP) scenarios (Rojas et al., 2013).

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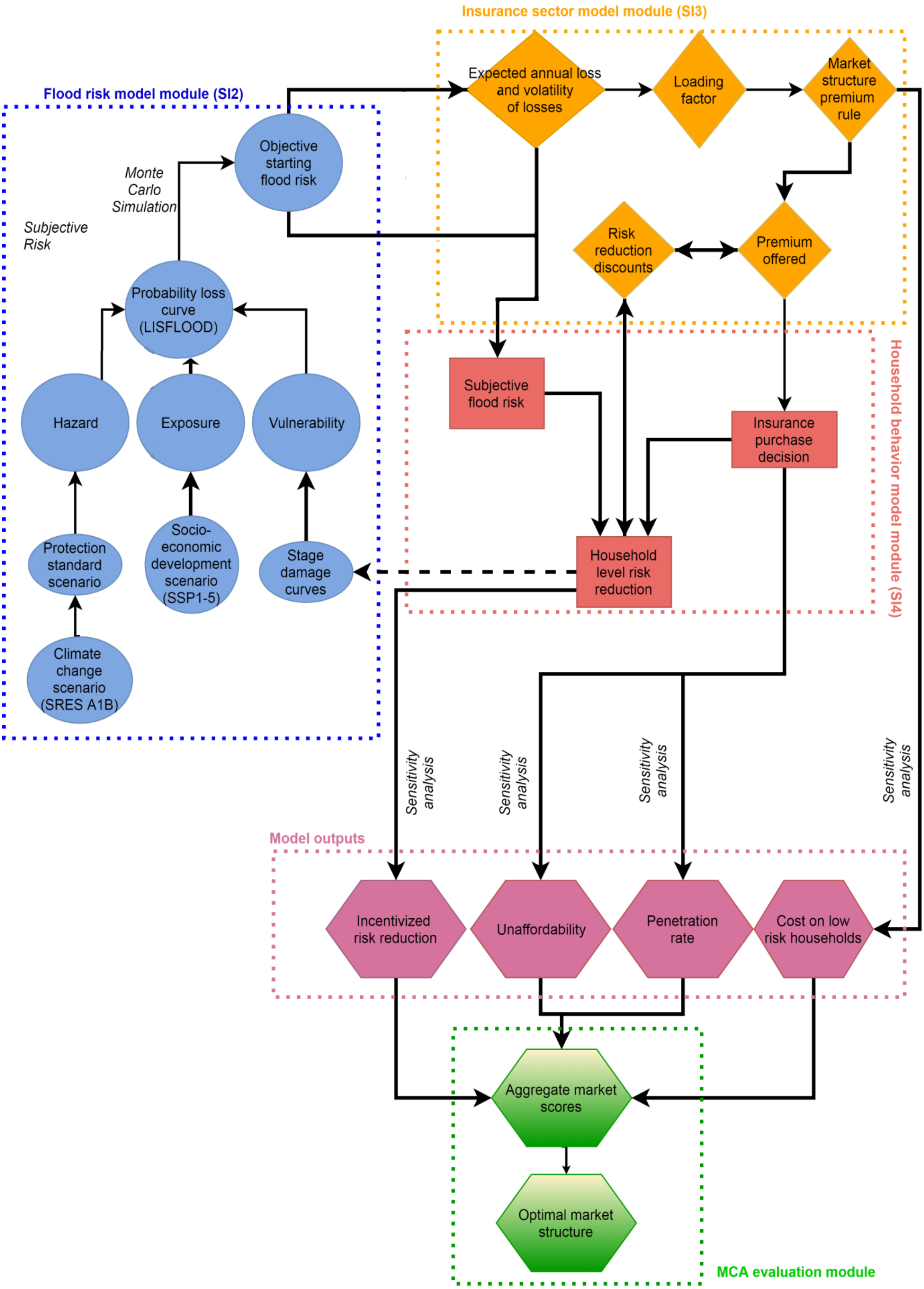
[2] A power law function takes the form $L = \tau_1 + \tau_2 p^{\tau_3}$.

[3] A Monte Carlo analysis was used to match the process to estimate the flood insurance purchase decision of households (SI4.1).

[4] Therefore, all estimated insurance premiums are in real terms.

Figure 1: Flow chart of the DIFI model version 1.0 modelling scheme



Note: Blue circles represent the flood risk model components, red diamonds represent insurer behaviour, red rectangles represent policyholder behaviour, and green hexagons represent the multi-criteria analysis. The combined flood risk model, insurer, and policyholder behaviour elements form the DIFI model.

The underlying hydrological-flood-damage model estimates the current and future risk of riverine floods across Europe at a 100m x100m (gridded) scale (Feyen et al., 2012; Rojas et al., 2013). However, the use of very detailed data would in practise entail high transaction costs for insurance companies as such information is not freely accessible (Osberghaus, 2015), which means that calculating premiums on this level may be infeasible (Porrini and Schwarze, 2014). Therefore, the estimated risk is aggregated to the NUTS 2 level, which is considered a suitable regional classification. Second, the obligation to buy insurance, along with the geographical size of the pool in which many risks are spread, eliminates concerns about adverse selection that may arise when premiums are set on an individual basis (see section 2.2).

Details of the flood risk modelling approach are provided in SI2.

2.2. Insurance sector (SI3)

We assume that each country under investigation has an insurance market that is willing to provide, and capable of providing, flood insurance to consumers as long as the consumer pays the offered premium. Moreover, we assume that the insurance policies offered provide sufficient coverage to avoid underinsurance. Due to this assumption, the DIFI model only captures underinsurance through lower penetration rates.

The insurance sector module uses the objective risk outcomes of the flood risk model to set insurance premiums (SI3.1), given the premium loading factors that depend on the market structure in which they operate (SI3.2). The primary insurance market (i.e., bought by households) is assumed to be highly competitive, whilst the reinsurance market (i.e., insurance bought by insurers) is assumed to be less so. Insurers will offer insurance premium discounts if a household employs risk mitigation measures. In all modelled insurance market structures, the insurance premium is calculated at the start of the year and is set at that value until the next year before considering household-level mitigation efforts. Only households that employ mitigation measures can receive premium discounts in line with the reduced risk (SI3.3).

We developed six flood insurance market structures (M1–M6), Table 2, based on information collected about European market structures (SI8) that reflect a range of market features. These are stylised market structures and, as such, capture the average performances and characteristics of a market structure. We focus on the market features that are important for generating the evaluation criteria. Therefore, there may be deviation between the stylised assumptions and what occurs in practise. However, a large-scale application, such as the DIFI model, inevitably requires that some details of current existing insurance market structures cannot be represented in the model. Nevertheless, this approach is in line with our aim to arrive at insights into general patterns across the European Union about the performance of flood insurance market structures in light of climate change and desirable reforms. Moreover, focussing the analysis on country-specific examples would not enable the study of potential counterfactual markets (e.g., France moving from a public solidarity-based market to a more private-sector-orientated market), whilst this is feasible with our stylised market structures.

The main structure of insurance premiums (across market structures) is based on Hudson et al. (2016), Paudel et al. (2013), and Paudel et al. (2015). Here, the premium which insurers charge households differs across market structures and takes the form displayed in eq. (2), where: $\pi_{i,j,t,s}$ represents the premium charged to household *i* in NUTS 2 region *j* at time *t* under market structure *s*, with *s* taking the value 1 for the solidarity market structure, 2 for the PPP market, 3 for the voluntary market structure, 4 for the semi-voluntary structure, and 5 and 6 are the semi, voluntary, and full PPP markets, respectively; ER_{DRR} is the discount that insurers will provide depending on the level of household risk reduction, which entails either one or both of dry and wet floodproofing, as described in section SI3.2; and $\bar{\pi}_{j,t,s}$ is the baseline average risk per household within a particular market structure for a given NUTS 2 region.

$$\pi_{i,j,t,s} = (1 - ER_{DRR})\bar{\pi}_{j,t,s} \tag{2}$$

The precise value of $\bar{\pi}_{j,t,s}$ differs across market structures, as shown in SI3. However, the key difference between market structures is how strongly $\bar{\pi}_{j,t,s}$ is connected to the risk that a household may face. A market with no connection to risk will have the lowest premiums for high-risk households, whilst one with a strong connection to risk is likely to have the highest premiums for these households. However, these premiums may be limited if households do implement risk-reducing measures.

Table 2: A summary of flood insurance structures

Structure group	Sector covering flood risk	Key market features	Potential insurance penetration rate (% with an insurance policy)	Risk sharing across high- and low-risk policyholders	Countries allocated
M1. Solidarity public structure	Public	Mandated purchase requirement Premiums unconnected to risk Government support for insurers No public flood damage compensation	Very high penetration rate (95–100%) due to direct purchase requirement	A high degree of risk sharing due to mandated purchase and non-risk-based premiums distributing risk widely	France, Belgium, Spain, Romania
M2. Semi-voluntary private market	Private	Purchase is connected to mortgage or rental conditions Premiums are risk based No government support for insurers No public flood damage compensation	High penetration rate (75–100%) due to indirect purchase requirements. Damage to buildings is more often insured than contents due to mortgage requirements.	A moderate degree of risk sharing due to indirectly mandated purchase and risk-based premiums	Sweden, Ireland, Hungary, Finland
M3. Voluntary private market	Private	No government-, product-, or dwelling-related mandated purchase requirement Premiums are risk based Possible public flood damage compensation	Medium to low penetration rates (0–60%) if government support is uncertain. Very low penetration rates (0–25%) if government support is certain.	A low degree of risk sharing due to voluntary purchase and risk-based premiums	Austria, Netherlands, Germany, Italy, Portugal, Luxembourg, Greece, Poland, Czech Republic, Slovakia, Slovenia, Croatia, Bulgaria, Latvia, Estonia, Lithuania
M4. Semi-voluntary PPP market	Public-Private	Same overall features as M2 except for the introduction of a government reinsurer for extreme risk. Private reinsurance remains available for less extreme events. Additionally, now there is no public flood damage compensation.	High penetration rate (75–100%) due to indirect purchase requirements	A moderate degree of risk sharing due to indirectly mandated purchase and risk-based premiums	Hypothetical market structure
M5. Voluntary PPP market	Public-Private	Same overall features as M3 except for the introduction of a government reinsurer for extreme risk. Private reinsurance remains available for less extreme events. Additionally, now there is no public flood damage compensation.	Medium to low penetration rate since premiums are lower than M3, so demand should be higher, given the presence of any public compensation in M3.	A low degree of risk sharing due to voluntary purchase and risk-based premiums	Hypothetical market structure
M6. Public-private partnership (PPP) market	Public-Private	Purchase is connected to mortgage lender or rental conditions. Premiums are partially risk based. Governmental frameworks to support insurers. No public flood damage compensation	High penetration rate (75–100%); higher than M2 due to the cap on the maximum premium size but lower than M1 due to a	Moderate to high degree of risk sharing but less than M1 due to indirectly mandated purchase and	UK

		stronger connection with risk	semi-risk-based premiums	

Note: Romania displays many of the criteria of M1 with the exception of the insurance penetration rate being less than 20 per cent due to poor enforcement of the purchase requirements. Therefore, it has been placed within M1 as a stylised market structure. See SI8.2 for details.

The proposed market structures are:

M1—*solidarity public structure:* All households must buy an insurance policy at a fixed price, regardless of their objective flood risk and personal preferences (e.g., an automatic extension of insurance policies). The premium is determined by equally sharing risks across all households (in a nation) regardless of their individual risk (SI3.1.1).

M2—The *semi-voluntary private market* is similar to the voluntary private market (SI3.1.3) except that mortgage, or rental, conditions have a requirement or tradition of comprehensive insurance coverage. However, coverage is not complete because those without mortgages are not compelled to insure. Although mortgaged buildings are almost universally insured, contents within a building are less often insured (Surminski and Eldridge, 2015), especially for low-income households (O'Neill and O'Neill, 2012; FEMA, 2018).

M3—*voluntary private market*: Households have the free choice of whether to buy flood insurance at risk-based premiums. Policyholders pay a premium in proportion to their annual expected loss, plus a surcharge covering insurer cost, profit, and risk aversion (SI3.1.3).

M4—*Semi-voluntary PPP* is similar to the semi-voluntary private market except that it is supported by a PPP. This is assumed to be a not-for-profit public reinsurer who charges a reinsurance premium for coverage. Introducing a public non-profit and risk-neutral reinsurer for a portion of risk will limit insurance premiums for households.

M5—*Voluntary PPP* has no purchase requirements and is similar to the voluntary private market except that it is supported by a not-for-profit public reinsurer.

M6—The *PPP market* is a compromise between M1 and M5. It connects insurance coverage with mortgage (or rental) conditions, it contains a public reinsurer (SI3.1.2), and premiums are risk based up to a threshold level at which the premium is capped (with possible surcharges to cover administrative costs). To maintain solvency, this shortfall is accounted for by placing a surcharge on the lower-risk households. This outcome can also be achieved by raising levies, similar to Flood Re. This organisation uses levies to generate a sufficient capital reserve that can be used to provide indemnity payments when the accessible financial resources prove insufficient.

Both private and public reinsurers charge a premium to primary insurers for the coverage they provide. However, reinsurers apply a premium surcharge due to their risk aversion (Paudel et al., 2015), whilst, due to the greater risk-spreading potential (e.g., taxation), public reinsurers are risk neutral and do not require a surcharge. However, providing public sector reinsurance facilities could be problematic as levels of risk aversion will vary amongst governments and are dependent on financial circumstances. Refocusing the European Union Solidarity Fund can be an alternative if it is reformed to act as a reinsurer or a co-insurance-style pool across the European Union. This would provide a great deal of geographical diversification, and such a reorientation is in line with a proposal directed towards the European Union Solidarity Fund in Hochrainer et al. (2010).

In each of the market structures above, the first role of the government is investing in risk-reduction infrastructure to maintain protection standards (see section 2.1). These flood protection standards keep flood probabilities constant under changing climate conditions, which is important for creating an environment for insurance markets to operate and maintain insurability of flood risk (Surminski and Thieken, 2017; Insurance Europe, 2018c; The Geneva Association, 2018).

The second role of the government occurs in M4 to M6, which are extensions of M1 to M3, in which the government acts as a reinsurer for the extreme element of flood risk that is expensive to reinsure privately (Paudel et al., 2015). Even though private-sector reinsurance is available, such coverage is more expensive compared to the publicly provided reinsurance. In all market structures, the government does not directly subsidise premiums.

A country is allocated to a stylised market based on how closely a market meets the following features: purchase requirements and the connection between premiums and risk. These points of comparison are the main aspects of the market that generate the four aforementioned evaluation criteria. This is because purchase requirements drive insurance penetration rates (Golnaraghi et al., 2017; Schanz, 2018), which can be influenced by legal obligations or by product design (Insurance Europe, 2018a) and the demand for non-insurance products (e.g., mortgages for which coverage is required). The link between premiums and risk can create trade-offs between affordability and the ability to incentivise risk reduction (Hudson et al., 2016). Finally, the combination of these two features determines the cross subsidy required between high- and low-risk policyholders.

Once an initial allocation has been made, the choice is refined based on the degree of government support available for the insurance industry and for households affected by flooding. For instance, public reinsurance (as is possible under M1) helps to keep premiums low by replacing potentially high private (risk-averse) reinsurance premiums with a lower public (risk-neutral) reinsurance premium. Also, the presence of government compensation can create a charity hazard which lowers the demand for insurance as the cost of not being insured is lower (Raschky and Weck-Hannemann, 2007). Both of these features are important for determining voluntary demand. Higher premiums can reduce the demand for insurance as the perceived benefits of insurance are smaller or the premium becomes unaffordable.

An assumption following from our assessment of fluvial flood risk is that flood insurance is treated as a stand-alone insurance product. However, flood insurance is often bundled with other natural hazard risks in countries with high penetration rates. In practise, such bundling often implies having semi-voluntary purchase requirements since flood coverage is commonly bundled with other risks like fire, for which it is compulsory to have coverage to meet mortgage requirements (see European Commission, 2017a, for example). Therefore, in our solidarity, semi-voluntary, and PPP markets, the insurance product could be considered part of a wider bundle of natural hazard risks. Bundling reduces the need for a conscious decision to buy a specific type of insurance. This is accounted for in our consumer behaviour model since, in semi-voluntary markets, flood insurance demand is not modelled as a conscious choice in an expected utility maximisation decision rule but instead as a fixed percentage that is calibrated based on observed penetration rates in these markets. Bundling could reduce the transparency of the insurance premium because it is based on a combination of risks, which may lower incentives for the policyholder to take measures to limit flood risk. This could be limited by better documentation of the risk elements that make up the premium and by reinforcing the link with property-level risk management, for example, by offering discounts to policyholders who take measures that limit their risk.

2.3. Household behaviour (SI4)

Details of the household behaviour modelling approach are provided in SI4 and are summarised here. Household behaviour consists of two decisions: to buy insurance (SI4.1) and to employ risk-mitigation measures (SI4.2).

A household makes an initial decision to undertake a risk mitigation measure based on the household's subjective level of flood risk and, as such, the perceived benefits of mitigation, which can be over- or underestimated. Next, the household makes a decision to buy insurance (M2 and M4) or is compelled to do so (the remaining market structures). Unless households are mandated to buy insurance, they will only buy insurance if the subjective expected utility of being insured is larger than the expected utility of not being insured and if the premium is affordable (SI4.1). The subjective expected utility framework is a model of individual decision making under risk (Savage, 1954). Households' risk perceptions are expected to deviate from objective risk in terms of flood occurrence probabilities and the potential damage suffered.

The subjective risk perceptions are calibrated based on previous studies, as noted in SI4.1–SI4.2. However, there is limited information available on the risk perceptions or mitigation behaviour of individuals across Europe. Therefore, we undertake a scenario approach in which we calibrate separate risk-perception distributions for simulating flood insurance demand and decisions to employ risk-reduction measures in the absence of insurance-based incentives. Perceptions of flood probability are based on empirical studies (Botzen et al., 2009; Botzen et al., 2015), and perceptions of flood damage follow a generalised Pareto distribution, both of which are calibrated to match regional insurance demand in Germany (GDV, 2013). Germany was selected for this since it provides the most detailed information within Europe about voluntary flood insurance purchases. The demand for household-level risk-reduction measures is based on a subjective cost-benefit analysis in which the benefits relate to the perceived reduction of flood risk by implementing a risk-reduction measure. This variable accounts for the possible misperceptions of the flood probability, the expected flood loss, and the potential effectiveness of the risk-reduction measure, and its distribution has been calibrated to match the observed usage of dry and wet floodproofing measures as reported in the following three studies: Kreibich et al. (2005), Bubeck et al. (2012), and Poussin et al. (2013). In the absence of detailed data at the European level, we create three risk perception scenarios. We focus on the average outcomes across these three risk perception scenarios in a similar way to how many flood risk assessment studies use ensemble climate model outcomes. However, this has the implication that the precise values of household behaviour resulting from these scenarios should be treated with caution. Nevertheless, the relative outcomes across the various scenarios and market structures may be less sensitive to uncertainty in this aspect of the model because each market is exposed to the same distributions of subjective risk perceptions.

A household with insurance coverage will be exposed to a potential premium discount if the household employs mitigation measures. This may promote a household to employ a mitigation measure if it did not do so initially. The more strongly premiums are risk based, the stronger this incentive will be (e.g., in the solidarity public structure, incentives are negligible). It should be noted that in some market structures and areas, the flood insurance premium, and hence the premium discount for taking risk-mitigation measures, is too low to act as an incentive to change policyholder behaviour. This can occur in areas with a low flood risk where employing flood risk-mitigation measures is not cost-effective. Moreover, this can happen in countries with a high degree of cross-subsidisation of premiums, which occurs in the solidarity market structure (M1). Both of these aspects are captured by our model, and indeed we find that the incentivised risk reduction through insurance is low in these market structures and in areas facing lower risk.

Moreover, there is an indirect interaction between household-level risk-reduction measures and the flood protection standards maintained by the government because the latter influence flood insurance premiums and the expected value of avoided flood damage by floodproofing measures. For instance, flood risk is low in areas with high flood protection standards, which results in lower premiums and lower benefits for household risk reduction in terms of either avoided flood damage or premium discounts compared to areas with low flood protection standards.

The household behaviour modelling approach is based on Hudson et al. (2016) and now includes budget constraints (SI4). The budget constraint implies that a household will only buy insurance if it is affordable to do so based on its income at the time of the decision. Including the budget constraint captures the tendency of higher-income households to be insured more often (Raschky et al., 2013). Insurance is deemed unaffordable when the premium to be paid is larger than the household's disposable income above the poverty line (Hudson et al., 2016; Zhao et al., 2016; FEMA, 2018). The total magnitude of insurance unaffordability is estimated as the sum of the unaffordable portion of insurance premiums (SI4.1). A similar budget constraint also applies to the employment of risk-reduction measures, where the measure is only taken if it is affordable at the time of purchase given any expenditure on insurance. The reason is that whilst a measure may be cost-effective in the long run, a household is unlikely to employ such a measure when it is currently unaffordable (SI4.2). This way, our model accounts for different capabilities between high- and low-income households to take flood risk adaptation measures. An implication is that insurance is only able to incentivise risk reduction if both the premium and the measure are affordable.

2.4. *Overall market evaluation (SI5)*

The MCA evaluation framework is based on the key evaluation criteria for the periods 2015–2035 and 2035–2055, as described in SI5. In an MCA framework, each of the key evaluation criteria can be associated with different weights as a measurement of the relative importance (trade-offs) that policymakers attach to one criterion as compared to the others.

The MCA method allows for identifying the relative benefits of the market structures and for finding the optimal market structures through a holistic comparative study of the evaluation criteria. The ensemble mean (across behaviour scenarios) of four criteria is aggregated from the NUTS 2 to the national level and standardised into a score for the structure within a country. This is done by creating a weighted sum across the four criteria for each market structure within a country.

In the MCA, the evaluation criteria are standardised and aggregated following eq. (3). ${S^1}_{c,s}$ is the score for market structure s in country c for the first period (or the second if ${S^2}_{c,s}$). The values for each indicator ($A^1_{c,s}$) are standardised since this allows the variables to have a common metric and to be weighted according to perceived importance.[5] The standardisation process bounds score values by 0 and 1.

$$
{S^1}_{c,s} = \frac{\sum_{n=1}^{n=11}\sum_{m=1}^{m=4}\omega_m^n MCA_{j,t,s}}{11}, \quad where\ MCA_{m,j,t,s} = \begin{cases} \frac{A^1_{c,s}-A^{1,Min}_{c,s}}{A^{1,Max}_{c,s}-A^{1,Min}_{c,s}} & if\ a\ benefit \\ 1-\frac{A^1_{m,j,t,s}-A^{1,Min}_{m,j,t,s}}{A^{1,Max}_{c,s}-A^{1,Min}_{c,s}} & if\ a\ cost \end{cases} \tag{3}
$$

The possible choices for $\{\omega_m^n\}$ can alter the overall attractiveness of the various market structures for each country. To account for the uncertainty in setting the weights, we use a range of weights to compare patterns of desirable market structures across different risk-management objectives. In particular, the following multiple sets of weights are used: (a) equal weights, where ω=1/4; (b) one element is weighted at ω=2/5 and the remaining two elements at ω=1/5 (with an alternating element with the double weight); and (c) two elements are weighted at ω=3/10 and the remaining elements at ω=1/5 (with alternating elements with the higher weight). There are eleven unique combinations of weights which reflect systematic differences in the importance of outcomes. These weights have been set by the authors to model outcomes under a range of potential public policy objectives described in SI8. The evaluation criteria and weights are applied equally to all the countries studied. Our approach is similar to the MCA employed in Unterberger et al. (2019) to model objectives for public-sector flood risk management in Austria. Our MCA identifies the market structure that, on average, scored the highest across the eleven sets of risk-management objectives (as proxy measured by the different weighting schemes) to indicate the optimal market. This approach assumes that one set of risk-management objectives is not treated as more important than another, the implications of which are discussed in section *4.2.2.5. Sensitivity analysis (SI6)*

An extensive sensitivity analysis was conducted, the results of which are presented in SI6, to find if the results are overall robust to changes in model structure or parameter values. In particular, the assumptions tested in the sensitivity analysis were: uncertainty in risk and insurance premium estimates (SI6.1), different flood risk scenarios (SI6.2), alternate construction of the insurance premium discount (SI6.3), using a single national pool of high-risk households rather than regional differentiation (SI6.4), alternative assumptions about the costs and effectiveness of risk-reduction measures (SI6.5), alternative

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[5] Whilst the mean score is presented in eq. (3) as the final indicator, using the median score does not produce noticeable differences.

assumptions on the utility function determining flood insurance demand (SI6.6), and a different MCA ranking scheme (SI6.7).

3. Results

3.1. Flood insurance reform pathways

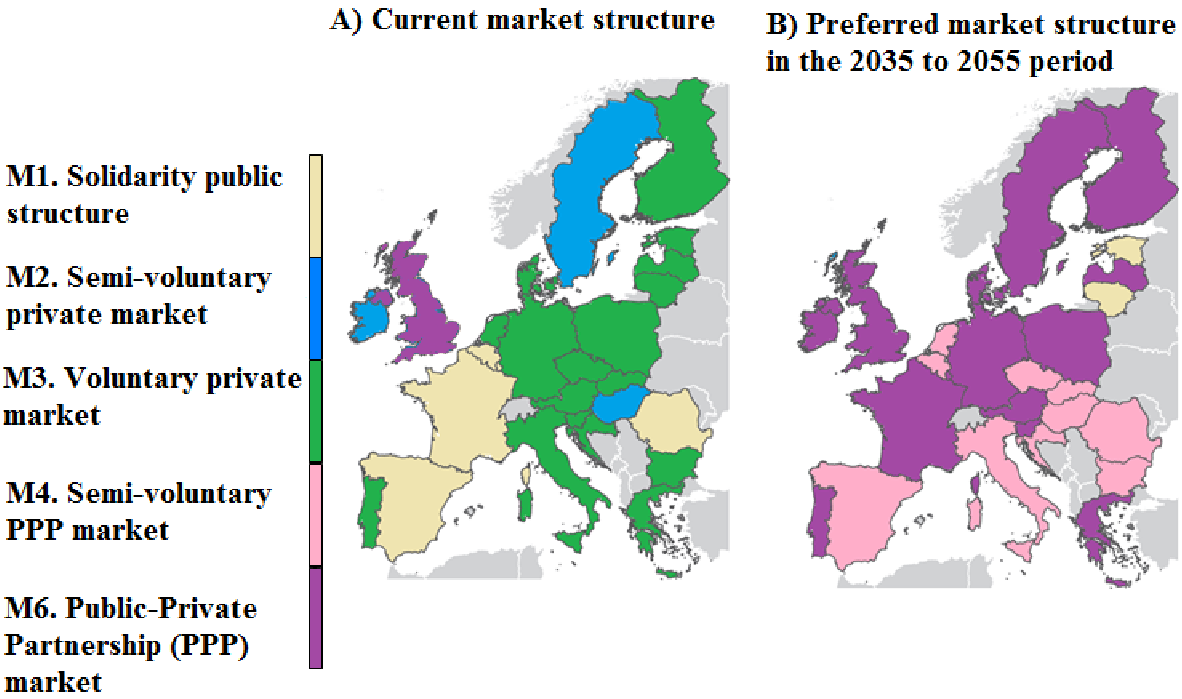
To our knowledge, this is the first large-scale study that integrates flood risk assessment, the insurance sector, and consumer behaviour in one modelling approach to assess insurance market structures against increasing flood risk. The DIFI model estimates that, on average, risk-based insurance premiums could double for the countries investigated between 2015 and 2055 if no flood insurance market reforms are undertaken. Hence, increasing flood risk will place pressures on stakeholders, such as insurers, to meet international agreements on disaster risk reduction, such as the Hyogo (Wilby and Keenan, 2012) and Sendai frameworks (UNISDR, 2015) and the Paris Agreement (UNFCC, 2018). Insurance could play an important role in providing both financial protection against flood losses and incentives for risk reduction. Flood insurance arrangements require reform to cope with increasing risk, and we demonstrate that household-level risk-reduction measures can be incentivised through a stronger link between risk reduction and the premiums charged. This finding highlights the importance of developing partnerships between the insurance sector and other flood risk management stakeholders to overcome the barriers to establishing an active link between premiums and risk reduction, for example, using certification schemes of floodproofing practises (Golnaraghi et al., 2017).

More precisely, the DIFI model output produces an average household insurance premium that is lowest in the solidarity public structure (€5–€125 per year in 2015) and highest in the private voluntary markets (€30–€2000 per year in 2015). These differences in premiums translate into different rates of unaffordability due to the differing degrees of cross-subsidisation between high- and low-risk households. For instance, the voluntary private insurance premiums are unaffordable for about 21 per cent of the regional population in high-risk areas (on average), whilst this is only 16 per cent in the PPP market (see SI7.1). However, the cost for low-risk households is lowest when premiums are based on risk with limited cross-subsidisation.

The risk mitigation incentives from insurance are not found to be effective in the solidarity public structure since the potential premium discount is too low (an average of €14 per year in 2055); see SI7.2. The voluntary market structures offer stronger incentives of, on average, €500 per year. However, fewer households are exposed to this incentive due to the lower market penetration rate of flood insurance. This is because the premium is unaffordable for many households, or it is perceived as being too high compared with the benefits of insuring. The PPP markets are found to be more successful in incentivising dry floodproofing than wet floodproofing measures due to their higher investment costs. Overall, insurance is more affordable in PPP markets, which also have a higher penetration rate that enables more risk reduction through the insurance incentives.

Figures 2A and 2B show how market structures would evolve from the current situation (2015) towards optimal structures for the period 2035–2055. During the 2015 to 2035 period, most countries are advised to move towards the semi-voluntary market (PPP) which entails reforms introducing public reinsurance and strengthening (indirect) purchase requirements. For the 2035 to 2055 period, the majority of countries will benefit from continued reform towards a full PPP market structure. For about a third of the countries, we estimate a reform pathway where the market structure evolves over time (see SI7.1).

Figure 2: Current flood insurance market structures (panel A) and market structure reforms suggested by the DIFI model for the period 2035-2055 (panel B)



This highlights that there may not be a single optimal market structure but a changing bundle of desirable features. Several studies have also argued that there is no one-size-fits-all solution for insurance markets (Surminski et al., 2016; Hochrainer-Stigler and Lorant, 2018; Raadgever et al., 2018). An example is the public response to the EC green paper on disaster insurance, which showed that many of the respondents were against the harmonisation of insurance regulations across the European Union (Surminski et al., 2015). Our study's focus, however, is on deriving general characteristics to guide reforms, and there are still many options for fine-tuning the exact method of implementation in a way that is in line with different preferences of local stakeholders. Moreover, there is not a single optimal market structure across periods and countries. Instead, we find that a process of continued reform over time is advisable for most of Europe: from the current market structure to the semi-voluntary PPP market and then towards the features of the PPP market.

Regardless of the absence of a single optimal market structure, altering market structures as suggested can improve the welfare of those living in flood-prone areas. This is because of the greater certainty in receiving suitable compensation after a flood or a greater sense of security due to being better prepared before a flood (See SI7.3). For instance, increased insurance coverage improves the welfare of a risk-averse household by exchanging an uncertain, and potentially catastrophic, loss from a flood for a certain, smaller payment in the form of an insurance premium. A higher market penetration of flood insurance can, therefore, be seen as welfare enhancing because of improved financial coverage against flood damage.

Moreover, from the policymaker perspective, uninsured flood impacts are undesirable as they are a driver of long-run negative macroeconomic impacts (Von Peter et al., 2012). Underinsurance is also a well-known issue in natural hazard insurance markets (The Geneva Association, 2018). For example, Austria has a penetration rate of nearly 85 per cent, but less than 10 per cent of the value exposed to flooding is insured (Insurance Europe, 2018b). In practise, coverage levels can vary amongst countries, which implies that flood insurance reforms should not only focus on obtaining a high market penetration but should also consider achieving sufficient coverage per policy. A closer collaboration of stakeholders in a PPP market can help to develop long-run mechanisms for limiting risks, like incentivising policyholder risk reduction, and for increasing coverage to limit the issue of underinsurance (Schanz, 2018; The Geneva Association, 2018).

The following findings are important for improving welfare: limited premium cross-subsidisation between high- and low-risk households, involvement of the government (or a transnational body) as reinsurer, incentives for policyholders to implement floodproofing measures to homes, purchase requirements such as mandating flood coverage, or connecting flood insurance coverage to mortgages or other more commonly acquired insurance policies such as fire. Such purchase requirements create a pool in which risks are shared between high- and low-risk households, and they also prevent adverse selection. The PPP market imposes lower costs on low-risk households than would occur under a solidarity market structure due to less premium cross-subsidisation between high- and low-risk households (see SI7.2). The PPP market manages to provide an acceptable trade-off between the unaffordability of risk-based premiums and the ability of such premiums to incentivise policyholders to employ risk-mitigation measures.

3.2. Optimal market structures

As noted, the semi-voluntary PPP (M4) and PPP (M6) markets most often score highest in the MCA. In particular, their stylised market features lead to higher average MCA scores, as compared to the voluntary or solidarity market structures. This means that these PPP markets have stylised features that best manage the trade-offs amongst the criteria for a given level of risk within a region.

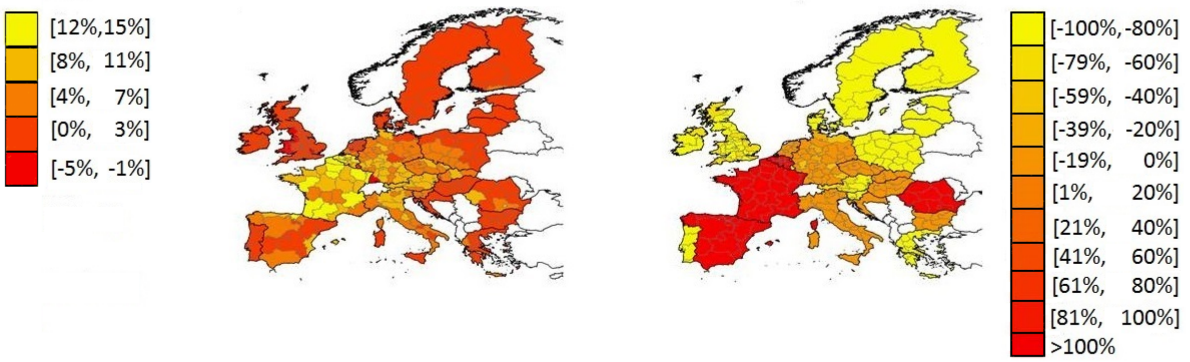
Although premiums are more often unaffordable and the penetration rates are slightly lower in the semi-voluntary PPP and PPP markets, these two markets score systematically better than the solidarity public structure (M1) because they perform significantly better in incentivising risk reduction by policyholders. Moreover, this additional incentivised risk reduction lowers the premium burden on households in lower-risk areas. Even though the final MCA score is determined by each element, the main driver of the performance of the semi-voluntary PPP and PPP markets is the increase in risk reduction, which outweighs the negative impacts of lower penetration rates and higher unaffordability. The main advantage of the semi-voluntary PPP and PPP market structures compared with the semi-voluntary market structure (M2) is that the two PPP structures have lower premiums and, hence, fewer problems with unaffordability of premiums.

Moreover, these two markets also perform better than the voluntary private (M3) or PPP (M5) market structures due to the higher penetration rate as a result of the indirect and direct purchase requirements. This has the effect that the risk-based premiums are able to incentivise additional risk reduction by many policyholders. The penetration rates under the voluntary markets are significantly lower, which implies few policyholders receive additional incentives to reduce risk through premium discounts. In the areas where the PPP market is preferred to the semi-voluntary PPP, the fully risk-based premiums in the latter market structure would increase premium unaffordability much more rapidly than they helped to promote additional risk reduction. The movement towards the PPP markets in this case indicates that slightly weakening the link between premiums and risk can reduce the burden of unaffordability whilst still promoting a sufficient degree of risk reduction. This combined effect results in an overall higher MCA score. The regions where the semi-voluntary PPP is preferred to the PPP have slightly lower risk overall, which means that a stronger link between risk and premiums is required to incentivise sufficient additional risk reduction.

3.3. Implication of proposed insurance reforms for risk mitigation and affordability of insurance

Figure 3 shows that moving towards the optimal stylised structures with varying degrees of PPPs results in an improvement in the amount of risk mitigation undertaken by households across most areas (Figure 3A) when premiums are (partly) risk based. The decision to floodproof properties under the existing market structures lowers residential risk on average by ~17 per cent from 2015 to 2055. The optimal insurance market structure increases this value to between 20 and 26 per cent due to stronger risk-mitigation incentives. Though these values are approximate, the key message is that strengthening insurance purchase requirements and policyholder risk mitigation can help to lower risk if the unaffordability concerns are alleviated.

Figure 3: Consequences of incentivised risk reduction (panel A) and unaffordability (panel B) of the insurance market reforms suggested by the DIFI model results for the year 2055, two elements of household welfare



A) Difference in incentivised risk reduction between starting market structure and the perferred structure in 2055

B) Percentage change in the magnitude of unaffordability between the starting market structure and the preferred structure in 2055

However, for the currently employed solidarity market structures, the reform towards increased mitigation incentives comes at the expense of insurance affordability for high-risk households whilst reducing the costs placed on low-risk households (Figure 3B). In contrast, for private insurance markets, the unaffordability of insurance outweighs the potential mitigation incentive of the insurance premiums. This implies that reform towards PPP is desirable. Unaffordability remains a concern even in the solidarity market structure, where the link between insurance and risk is weakest. This suggests that overcoming problems with unaffordability may require the use of public policies such as insurance vouchers for low-income households in high-risk areas (Kunreuther, 2008). An insurance voucher is provided by the government to low-income households for the proportion of the insurance premium deemed to be unaffordable. The vouchers are issued on a temporary basis to smooth the transition to new market structures. Whilst vouchers can ease the cost that high premiums place on low-income households, the vouchers should remain temporary to prevent an implicit subsidy for development in flood-prone areas (Kousky and Kunreuther, 2014).

Another way to improve affordability is to increase the sharing of losses over many policyholders through the introduction of purchase requirements. This policy reform expands the risk pool of insured households, which lowers premiums. Moreover, purchase requirements limit the threat of asymmetric information to cause market failures through adverse selection.

However, the introduction of purchase requirements, like in the PPP market, may also be politically difficult because it can be seen to limit consumer freedom. This issue is substantiated by discussions regarding insurance reforms in the Netherlands (Botzen, 2013) and Germany (Schwarze and Wagner, 2007). Additionally, conflicts with state aid regulations can arise. This can be seen from the United Kingdom’s introduction of Flood Re, which would be partially funded by an industrywide levy. This planned reform received criticism as it would confer an economic advantage to the risk pool over its competitors, which conflicts with the European Union’s state aid regulations (European Commission, 2015). Nevertheless, this was decided not to be the case, although it still acted as an additional hurdle.

The use of public reinsurance can also limit insurance premiums and, thereby, partly overcome problems with coverage unaffordability. Our evaluation over time shows that this is especially attractive when flood risks increase. Risk-averse insurers increase their premiums when low-probability/high-impact risks increase, especially when these risks are uncertain (Michel-Kerjan and Kunreuther, 2011), as is the case with flood risk in a changing climate (IPCC, 2012). It may be argued that governments can more cheaply reinsure extreme losses (Cardenas et al., 2007) because European governments are, for the most part, risk neutral. Moreover, we find that a public reinsurance facility does not interfere too strongly with the underlying risk signal and incentives for risk reduction. This is the case because primary insurers pay for the government support they receive though risk-based reinsurance premiums, and this reinsurance premium is, in the end, reflected in the premium that households pay. Another advantage of this payment structure is that the government (and thereby taxpayers overall) receives a fair share of compensation for provided reinsurance. However, risk-based premiums imply that high premiums can occur in areas with a high flood risk when premiums are risk based and people do not mitigate risk, which implies that these premiums could not be affordable or economically viable. This can be overcome in the PPP market structure which places a cap on premiums.

3.4. Sensitivity analysis

The results of the sensitivity analysis show that the overall pattern of our main findings is in line with the main assumptions of the model (SI6). The results consistently confirm the desirability of the features common to the semi-voluntary PPP and PPP market structures. The link between premiums and risk reduction in these structures was found to be very important. When this link was removed, the optimal market structure became the solidarity market structure in all cases. This shows that strengthening the link between insurance and risk reduction is important for the continued use of private insurance in the future, when flood risk increases due to climate change. Moreover, the stronger the projected increase in flood risk, the more often the PPP market structure was found to be optimal (SI7.1), indicating the importance of increasing the role of PPPs, both for sharing flood risk and developing institutional frameworks for promoting risk reduction.

The current version of the DIFI model can be updated as more localised or updated information becomes available. Moreover, by comparing the patterns of relative scores rather than specific values, the final recommendations are more robust. One such finding is that strengthening the link between risk-based insurance and risk mitigation is important for keeping premium costs low.

4. Discussion

4.1. Policy implications

Our findings have relevance to policies in specific countries. For instance, there is some similarity between the PPP market and the United Kingdom's recently introduced Flood Re. Both are based on the mandated purchase of insurance through mortgage conditions with an explicit subsidy for high-risk households. The latter is implemented in Flood Re by charging a supplement on the premiums of low-risk households of approximately £10.50 on average per year, which is close to the estimated cost of €18 (£15) per household per year imposed on low-risk households by the DIFI model. However, we find that the current structure of Flood Re is not optimal for the United Kingdom since incentives for risk reduction are absent. This supports previous research on the matter (Surminski, 2017). The experience with Flood Re also shows that the political motivation to provide public reinsurance coverage can be limited in practise since Flood Re has purchased private-reinsurance-sector coverage.

The solidarity-based market structures of Belgium, France, and Spain are also in need of reform. The reason is that their current market structures may not be suitable for coping with future increases in flood risk due to insufficient incentives for risk reduction. The solidarity principle concerning flood insurance in these countries may be better served by stimulating risk reduction through risk-based premiums whilst addressing equity concerns using additional public policies (e.g., means-tested insurance vouchers or tax credits). The remaining countries with a voluntary purchase requirement (e.g., Germany) should consider promoting or strengthening purchase requirements as, otherwise, the penetration rate remains low, preventing many of the benefits of insurance as a risk-management tool from being realised. For instance, in Hungary, the insurance penetration rate has been increased by making flood insurance coverage a prerequisite to obtain a mortgage (European Commission, 2017a).

Our main policy recommendations may also be applicable outside of Europe. For instance, the National Flood Insurance Program (NFIP) in the United States has undergone many potential reforms, such as the Biggert-Waters Flood Insurance Reform Act of 2012, the Homeowners Flood Insurance Affordability Act of 2014, and the Flood Insurance Market Parity and Modernization Act of 2016.

These acts are aimed at improving the financial sustainability of the NFIP. Moreover, these reforms aim to improve the actuarial soundness of the program by moving towards risk-based premiums whilst strengthening purchase requirements to overcome the observed low penetration rate outside high-risk areas and improving incentives for risk reduction. Michel-Kerjan and Kunreuther (2011) propose a set of reforms for the NFIP similar to those we find favourable for most European countries based on the DIFI model analysis. However, in both cases, these are high-level features of a market structure. Therefore, their implementation will require suitable localisation for them to be politically acceptable and practicable.

Even though we acknowledge that community- and national-level risk-reduction efforts are important for adapting to changing flood risk under climate change, our model mainly focusses on household-level risk reduction and how this can be steered with premium discounts. This is because the incentives provided by premium discounts are commonly discussed advantages of moving towards risk-reflective premiums in the context of flood insurance market reforms around the world, e.g., Flood Re (2018), Lamond et al. (2018), Thieken (2018), European Commission (2017b), and Kunreuther (2017). Moreover, our focus is consistent with a movement towards integrated flood risk management in which residents of flood-prone areas are expected to play a role in limiting flood damage (Bubeck et al., 2016). Our modelling framework shows that human behaviour is an important factor when assessing flood risk, which is in line with recent calls for integrating human behaviour into risk assessments (Aerts et al., 2018b). Although we find that exposure growth is a factor that causes flood risk to rise, the floodproofing of properties by households can limit this increase in risk. Efforts to reduce risk are stronger when they are actively incentivised through insurance. For this reason, we study the potential benefits of increasing the connection between risk mitigation and insurance.

However, there is often a concern that, in practise, links between insurance and policyholder-level risk mitigation are insufficient (Surminski et al., 2015). This is commonly argued to be caused by transaction costs involved in insurers monitoring policyholders on a large scale and adjusting premiums accordingly (Hudson et al., 2016). However, this barrier could be overcome if insurers collaborate with other organisations, for example, those that certify the floodproofing of buildings (similar to the home elevation certificates used in the United States), which emphasises the need for closer partnerships (Kunreuther, 2015a). These PPPs are also highly relevant for increasing other aspects of societal resilience. Examples are information sharing about risk and risk-reduction measures, awareness-raising campaigns, offering incentives for risk reduction through terms and policy conditions, setting standards for insurability, and building codes. These are areas in which collaboration between insurance and public-sector stakeholders can not only influence risk reduction behaviour but also risk-generating behaviour, for example, by limiting exposure growth through building codes and zoning policies. Our proposed PPP flood insurance market structures can provide a platform for enabling such integrated flood risk management approaches.

4.2. Model limitations

Although the DIFI model framework enables the evaluation of flood insurance markets across Europe, there are several limitations regarding the interpretation of the results. However, addressing these issues can provide directions for future research.

One limitation is that the modelled insurance market structures are stylised representations of a more complex reality as these do not reflect the individual nuances of the insurance market in each country. The current DIFI model framework limits the complexity of insurance markets by focussing on the market features that have a large influence on the modelled evaluation criteria, such as purchase requirements, the connection of premiums with risk, and the availability of public reinsurance. A challenge is that implementing a higher degree of complexity requires that data on these additional details should be available at the European scale, which is often not the case or is potentially outdated (European Commission, 2013, 2017a, b). For example, insurance coverage levels are difficult to collect and determine due to the unavailability of standardised measures of flood insurance products and their coverage across the European Union (European Commission, 2017b). This can be an important practical limitation because penetration rates in a country could be high, but the total coverage offered by flood insurance can be low, as is the case in Austria (see Insurance Europe (2018b)). However, we attempt to limit the uncertainty from the stylised market structures by mainly looking at the relative benefits of the market structures and the lessons we can learn for 2035–2055 from the overall patterns of desirable reforms we observe. This choice means that the overall implications are less dependent on the original allocation of a country to a stylised market structure.

Similar data limitations apply to individual risk perceptions and adaptation behaviour in household responses to changes in flood risk. For example, to the best of our knowledge, there are no studies linking flood risk perceptions and household-level risk reduction for the Eastern Baltic countries. Therefore, in line with the increasing focus on behaviour in flood risk modelling and management (see, e.g., Aerts et al. (2018)), a wider evidence base on these variables must be developed. The reason is that there is limited knowledge on how subjective perceptions or adaptation behaviours occur across Europe, which must be improved by future research (Aerts et al., 2018). This is especially relevant with respect to the limited temporal dimensions of the available datasets as most studies on risk perception and adaptation behaviour use cross-sectional data collected at one point in time. Nevertheless, even with additional data collection, there will be inherent limitations to validating household-level risk-reduction behaviour and insurance-purchasing patterns at the European scale due to the counterfactual nature of several of the modelled market structures. For example, France has employed a compulsory insurance system since the 1980s (Poussin et al., 2013), which means there is no empirical information about voluntary flood insurance purchases there. The current DIFI framework addresses these uncertainties by using three different risk perception scenarios based on available data. This is done in a similar way to how climate modelling often focusses on the ensemble mean values of a range of models. Moreover, the model focusses mainly on determining and comparing overall patterns in the results between insurance market structures rather than focussing on the absolute value estimates.

Another uncertainty arises from the weights associated with each of the evaluation criteria in our MCA. Currently, we apply general patterns of these weights across the European Union, although they can differ at the country level because of varying local flood risk management objectives. For example, within a specific country, the penetration rate and affordability criteria could be weighted at 0.5 each, whilst the remaining two criteria could be weighted at zero. A weighting scheme like this would find the solidarity market optimal, whilst reversing this particular weighting results in the semi-voluntary (PPP) and PPP markets becoming optimal. Therefore, stakeholder consultation within each country is required to adapt the findings of the DIFI model to their individual context. The current DIFI framework seeks to mitigate this limitation by focussing on overall patterns found across a range of synthetic risk management objectives and how these may be applicable to specific countries.

5. Conclusions

The combined effects of socioeconomic development and climate change are expected to increase flood risk in many areas across the world. This growing risk profile has resulted in an increased interest in strategies that can help manage and limit the impacts of flooding. The development of suitable flood insurance mechanisms is one such strategy. Various countries have debated which kind of flood insurance arrangement is best able to cope with future changes in flood risk. To provide insights for this debate, we presented an initial comparative evaluation of stylised flood insurance market structures for Europe through the DIFI model framework, which is a holistic evaluation method of flood insurance arrangements using four important criteria.

The results of the comparative DIFI model suggest a common insurance market reform pathway for insurance as a flood risk management tool with the following features: limited premium cross-subsidisation between high- and low-risk households, involvement of a governmental reinsurer, incentives for policyholders to floodproof homes, and stronger purchase requirements. Even though there is no one-size-fits-all solution, there are common features which can guide local discussions on reforms for flood insurance markets. These common features, such as the movement towards a greater focus on PPPs, involving a range of stakeholders, can lead to the creation of mechanisms that support households to buy insurance and support the insurance industry to provide a wider degree of coverage.

Moreover, due to the focus on stylised market characteristics, our recommendations are applicable outside of Europe. Even though the overall patterns of stylised flood insurance market characteristics appear to be generalisable, their practical implementation will have to be tailormade according to local risk profiles and public policy preferences (Raadgever et al., 2018).

Several areas of future research were identified based on the development and application of the DIFI model framework. The primary focus of risk reduction has been on the role of premium discounts for households, whilst it is also possible to influence the risk behaviour of governments and businesses through insurance. There are initial steps in this direction (see, e.g., Unterberger et al. (2019)), and future research in this area should be further developed. Additionally, residential flood insurance only protects against certain elements of overall flood impacts, although there are also large potential impacts through the disruption of infrastructure, governmental services, and so forth which can be addressed in future studies.

Furthermore, future research can examine the most cost-effective ways of reducing the transaction costs involved in stimulating policyholder risk-reduction behaviour through risk-based premiums, e.g., using certification of floodproof building practises. Moreover, mechanisms other than premium discounts may be effective in promoting risk reduction, which can be evaluated in future studies. An example is that insurers may raise policyholders' risk awareness by better informing them about the flood risk they face. In relation to this point, improving knowledge about individual flood risk perceptions across Europe and how these may be influenced by risk communication campaigns could strengthen the empirical basis of this component in the DIFI model.

A common finding of the DIFI model is that PPPs stand to play a large role in future flood insurance reforms. The above research suggestions can build upon this finding by extending the range of partners involved to create a suitable enabling environment to strengthen the link between insurance and risk reduction (see, for example, discussions presented in Flood Re (2018), Surminski and Thieken (2017), or The Geneva Association (2018)).

Finally, the focus of this paper was on fluvial flooding, but in the light of climate change and increasing urbanisation, coastal and pluvial flood risks stand to grow in importance. Thus, future research can focus on understanding how these particular flood risks can be integrated into a modelling framework like DIFI. This distinction is important because coastal flooding and adaptation follow a different process to fluvial flooding, whilst pluvial flooding processes follow localised phenomena. In general, we believe that future research on multi-hazard risk assessments can offer a useful basis for insurance modelling and adaptation studies.

References

Aerts, J.C.J.H., Botzen, W., Clarke, K.C., Cutter, S.L., Hall, J.W., Merz, B., Michel-Kerjan, E., Mysiak, J., Surminski, S., Kunreuther, H. (2018) Integrating human behaviour dynamics into flood disaster risk assessment. Nature Climate Change 8, 193-199.

Alfieri, L., Dottori, F., Betts, R., Salamon, P., Feyen, L. (2018) Multi-Model Projections of River Flood Risk in Europe under Global Warming. Climate 6, 6.

Baur, E., (2016) The role of insurance in disaster risk financing, IDRC, Davos, CH.

Botzen, W.J.W. (2013) Managing Extreme Climate Change Risks Through Insurance. Cambridge University Press, New York.

Botzen, W.J.W., Aerts, J.C.J.H., van den Bergh, J.C.J.M. (2009) Dependence of flood risk perceptions on socioeconomic and objective risk factors. Water Resources Research 45.

Botzen, W.J.W., Kunreuther, H., Michel-Kerjan, E. (2015) Divergence between individual perceptions and objective indicators of tail risks: Evidence from floodplain residents in New York City. Judgment and Decision Making 10, 365-385.

Bubeck, P., Aerts, J.C.J.H., de Moel, H., Kreibich, H. (2016) Preface: Flood-risk analysis and integrated management. Natural Hazards and Earth Systems Science 16, 1005-1010.

Bubeck, P., Botzen, W.J.W., Kreibich, H., Aerts, J.C.J.H. (2012) Long-term development and effectiveness of private flood-risk reductions: an analysis for the German part of the river Rhine. Natural Hazards and Earth Schemes Science 12, 3507-3518.
Cardenas, V., Hochrainer, S., Mechler, R., Pflug, G., Linnerooth-Bayer, J. (2007) Sovereign financial disaster risk management: The case of Mexico. Environmental Hazards 7, 40-53.
CRED-UNISDR, (2015) The human cost of weather related disasters, 1995–2015. Centre for research on the epidemiology of disasters and United Nations office for disaster risk reduction.
Cremades, R., Surminski, S., Máñez Costa, M., Hudson, P., Shrivastava, P., Gascoigne, J. (2018) Using the adaptive cycle in climate-risk insurance to design resilient futures. Nature Climate Change 8, 4-7.
DEFRA, (2011) Flood risk and insurance: a roadmap to 2013 and beyond final report of the flood insurance working groups PB 13684. Department for Environment, Food and Rural Affairs, London.
European Comission, (2013) Green Paper on the insurance of natural and man-made disasters (Communication No. COM(2013) 213 final). European Commission, Strasbourg.
European Comission, (2017a) Insurance of weather and climate-related disaster risk: Inventory and analysis of mechanisms to support damage prevention in the EU, in: Le Den, X., Persson, M., Benoist, A., Hudson, P., de Ruiter, M., de Ruig, L., Kuik, O., Botzen, W. (Eds.). Publications Office of the European Union, Luxembourg.
European Comission, (2017b) Study to support the evaluation of the EU adaptation stratergy, summary. European Comission.
European Commission, (2015) State aid: Commission approves UK flood reinsurance scheme, in: Cardoso, R., Ren, Y. (Eds.), IP-15-3884_EN. European Commission, Brussels.
FEMA (2016) Special Flood Hazard Area, http://www.fema.gov/special-flood-hazard-area, .
FEMA, (2018) An affordability framework for the National Flood Insurance Program. Department of Homeland Security, Washington, DC.
Feyen, L., Dankers, R., Bódis, K., Salamon P., Barredo, J.I. (2012) Fluvial flood risk in Europe in present and future climates. Climatic Change 112, 47-62.
Flood Re, (2018) INCENTIVISING HOUSEHOLD ACTION ON FLOODING AND OPTIONS FOR USING INCENTIVES TO INCREASE THE TAKE UP OF FLOOD RESILIENCE AND RESISTANCE MEASURES. Flood Re.
GDV (2013) Naturgefahrenreport 2013 - Die Schaden-Chronik der deutschen Versicherer mit Zahlen,Stimmen und Ereignissen. German Insurance Association (GDV) (2013), available at: http://bit.ly/1i7Ich2.
Golnaraghi, M., Surminski, S., Schanz, K., (2017) An intergrated appraoch to managing extreme events and cliamte risks. . The Geneva Assocaition, Zurich.
Hochrainer-Stigler, S., Lorant, A. (2018) Evaluating Partnerships to Enhance Disaster Risk Management using Multi-Criteria Analysis: An Application at the Pan-European Level. Environmental Management 61, 24-33.
Hochrainer, S., Linnerooth-Bayer, J., Mechler, R. (2010) The European Union Solidarity Fund. Mitigation and Adaption Strategies for Global Change 15, 979-810.
Hudson, P. (2018) A comparison of definitions of affordability for flood risk adaption measures: A case study of current and future risk-based flood insurance premiums in Europe. Mitigation and Adaptation Strategies for Global Change 23, 1019-1038.
Hudson, P., Botzen, W.J.W., Feyen, L., Aerts, J.C.J.H. (2016) Incentivising flood risk adaptation through risk based insurance premiums: trade-offs between affordability and risk reduction. Ecological Economics 125, 1-13.
Insurance Europe, (2018a) Insurance and natural catastrophes Insurance Europe, Brussels.
Insurance Europe, (2018b) NatCat Chart — Property Insurance, Private lines. Insurance Europe, Brussels.
Insurance Europe, (2018c) Response to the European Commission's consultation on the evaluation of the EU's strategy on adaptation to climate change. Insurance Europe.
IPCC (2012) Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, USA.
IPCC, (2018) Global Warming of 1.5C. IPCC, Switzerland.

Johnson, C., Penning-Rowsell, E., Parker, D. (2007) Natural and Imposed Injustices: The Challenges in Implementing 'Fair' Flood Risk Management Policy in England. The Geographical Journal 173, 374-390.
Jongman, B., Hochrainer-Stigler, S., Feyen, L., Aerts, J.C.J.H., Mechler, R., Botzen, W.J.W., Bouwer, L., Pflug, G., Rojas, R., Ward, P.J. (2014) Increasing stress on disaster-risk finance due to large floods. Nature Climate Change 4, 264-268.
Kousky, C., Kunreuther, H. (2014) Addressing Affordability in the National Flood Insurance Program. Journal of Extreme Events 1, 1450001.
Kousky, C., Kunreuther, H., Lingle, B., Shabman, L., (2018) The Emerging Private Residential Flood Insurance Market in the United States, Wharton Risk Management and Decision Processes Center Wharton, Risk Management and Decision Procecsses Center, University of Pennsylvania, Philadelphia, US.
Kreibich, H., Thieken, A.H., Petrow, T., Müller, M., Merz, B. (2005) Flood loss reduction of private households due to building precautionary measures- lessons learned from the Elbe flood in August 2002. Natural Hazards and Earth Schemes Science 5, 117-126.
Kron, W. (2005) Flood Risk = Hazard • Values • Vulnerability. Water International 30, 58-68.
Kunreuther, H. (2008) Reducing Losses from Catastrophic Risks through Long-term Insurance and Mitigation. ´Social Research 75, 905-930.
Kunreuther, H. (2015a) The role of insurance in reducing losses from extreme events: The need for public-private partnerships. The Geneva Papers on Risk and Insurance Issues and Practice 40, 741-762.
Kunreuther, H. (2015b) The role of insurance in reducing losses from extreme events: The need for public-private partnerships. The Geneva Papers on Risk and Insurance Issues and Practice 40, 471.
Kunreuther, H., (2017) Encouraging Adaptation to Flood Risk: The Role of the National Flood Insurance Program, Wharton Working Papers. Wharton, University of Pennsylvania, Philadelphia, USA.
Lamond, J., Rose, C., Bhattacharya-Mis, N., Joseph, R., (2018) EVIDENCE REVIEW FOR PROPERTY FLOOD RESILIENCE PHASE 2 REPORT. Flood Re and UWE Bristol.
Lamond, J.E., Penning-Rowsell, E.C. (2014) The robustness of flood insurance regimes given changing risk resulting from climate change. Climate Risk Management 2, 1-10.
Mechler, R., Bouwer, L.M., Linnerooth-Bayer, J., Hochrainer-Stigler, S., Aerts, J.C.J.H., Surminski, S., Williges, K. (2014) Managing unnatural disaster risk from climate extremes. Nature Climate Change 4, 235-237.
Michel-Kerjan, E., Czajkowski, J., Kunreuther, H. (2015) Could flood insurance be privatised in the United States? A primer. The Geneva Papers on Risk and Insurance Issues and Practice 40, 179-208.
Michel-Kerjan, E., Kunreuther, H. (2011) Redesigning flood insurance. Science 333, 408-409.
O'Neill, J., O'Neill, M., (2012) Social justice and the future of flood insurance, in: Foundation, J.R. (Ed.), York, UK.
Osberghaus, D. (2015) The determinants of private flood mitigation measures in Germany — Evidence from a nationwide survey. Ecological Economics 110, 36-50.
Paudel, Y., Botzen, W.J.W., Aerts, J.C.J.H. (2013) Estimation of insurance premiums for coverage against natural disaster risk: an application of Bayesian Inference. Natural Hazards and Earth Schemes Science 13, 737-754.
Paudel, Y., Botzen, W.J.W., Aerts, J.C.J.H., Dijkstra, T. (2015) Risk allocation in a public-private catastrophe insurance system: an actuarial analysis of deductibles; stop-loss; and premium. Journal of Flood Risk Management 8, 116-134.
Porrini, D., Schwarze, R. (2014) Insurance models and European climate change policies: an assessment. European Journal of Law and Economics 38, 7-28.
Poussin, J.K., Botzen, W.J.W., Aerts, J.C.J.H. (2013) Stimulating flood damage mitigation through insurance: an assessment of the French CatNat system. Environmental Hazards 12, 258-277.
Raadgever, G.T., Booister, N., Steenstra, M.K., (2018) Flood Risk Management Strategies, in: Raadgever, T., Hegger, D. (Eds.), Flood Risk Management Strategies and Governance. Springer International Publishing, Cham, pp. 93-100.
Raschky, P.A., Schwarze, R., Schwindt, M., Zahn, F. (2013) Uncertainty of Governmental Relief and the Crowding out of Flood Insurance. Environmental Resource Economics 54, 179-200.

Raschky, P.A., Weck-Hannemann, H. (2007) Charity hazard—A real hazard to natural disaster insurance? Environmental Hazards 7, 321-329.
Rojas, R., Feyen, L., Watkiss, P. (2013) Climate change and river floods in the European Union: Socio-economic consequences and the costs and benefits of adaptation. Global Environmental Change 23, 1737-1751.
Savage, L.J. (1954) The Foundation of Statistics. John Wiley, New York.
Sayers, P., Penning-Rowsell, E.C., Horritt, M. (2018) Flood vulnerability, risk, and social disadvantage: current and future patterns in the UK. Regional Environmental Change 18, 339-352.
Schanz, K., (2018) Understanding and Addressing Global Insurance Protection Gaps, Research in brief The Geneva Assocation Zurich, CH.
Schwarze, R., Wagner, G.G. (2007) The political economy of natural disaster insurance: Lessons from the failure of a proposed insurance scheme in Germany. Environmental Policy and Governance 17, 403-415.
Surminski, S., (2017) Fit for Purpose and Fit for the Future? An Evaluation of the UK's New Flood Reinsurance Pool. Resources for the Future.
Surminski, S., Aerts, J.C.J.H., Botzen, W.J.W., Hudson, P., Mysiak, J., Pérez-Blanco, C.D. (2015) Reflection on the current debate on how to link flood insurance and disaster risk reduction in the European Union Natural Hazards 79, 1451-1479.
Surminski, S., Bouwer, L., Linnerooth-Bayer, J. (2016) How insurance can support climate Resilience. Nature Climate Change 6, 333-334.
Surminski, S., Eldridge, J. (2015) Flood insurance in England: an assessment of the current and newly proposed insurance scheme in the context of rising flood risk. Journal of Flood Risk Management.
Surminski, S., Thieken, A. (2017) Promoting flood risk reduction: The role of insurance in Germany and England. Earth's Future 5, 979-1001.
Thaler, T., Fuchs, S., Priest, S., Doorn, N. (2018) Social justice in the context of adaptation to climate change—reflecting on different policy approaches to distribute and allocate flood risk management. Regional Environmental Change 18.
Thaler, T., Hartmann, T. (2016) Justice and flood risk management: reflecting on different approaches to distribute and allocate flood risk management in Europe. Natural Hazards 83, 129-147.
The Geneva Association, (2018) Climate Change and the Insurance Industry: Taking Action as Risk Managers and Investors Perspectives from C-level executives in the insurance industry. The Geneva Association.
Thieken, A., (2018) Contributions of flood insurance to enhance resilience–findings from Germany, in: Fekete, A., Fiedrich, F. (Eds.), Urban Disaster Resilience and Security. Springer, pp. 129-143.
UNFCC, (2018) Paris Agreement. UNFCC.
UNISDR, (2015) Sendai Framework for Disaster Risk Reduction 2015-2030. United Nations, United Nations - Headquarters (UN).
Unterberger, C., Hudson, P., Botzen, W.J.W., Schroeer, K., Steininger, K.W. (2019) Future Public Sector Flood Risk and Risk Sharing Arrangements: An Assessment for Austria. Ecological Economics 156, 153-163.
Von Peter, G., von Dahlen, S., Saxena, S., (2012) Unmitigated Disasters? New Evidence on the Macroeconomic Cost of Natural Catastrophes, BIS Working Papers No. 394, Basel: Bank for International Settlements (BIS).
Vousdoukas, M.I., Mentaschi, L., Voukouvalas, E., Bianchi, A., Dottori, F., Feyen, L. (2018) Climatic and socioeconomic controls of future coastal flood risk in Europe. Nature Climate Change 8, 776-780.
Wilby, R.L., Keenan, R. (2012) Adapting to flood risk under climate change. Progress in Physical Geography 36, 348-378.
Winsemius, H.C., Aerts, J.C.J.H., van Beek, L.P.H., Bierkens, M.F.P., Bouwman, A., Jongman, B., Kwadijk, J.C.J.K. (2016) Global Drivers of Future River Flood Risk. Nature Climate Change 6, 381-385.
Zhao, W., Kunreuther, H., Czajkowski, J. (2016) Affordability of the National Flood Insurance Program: Application to Charleston County, South Carolina. Natural Hazards Review 17, 1-14.

Online Supplementary Information

SI1. Dynamic Integrated Flood Insurance (DIFI) model algorithm

The Dynamic Integrated Flood Insurance (DIFI) model is used for modelling the outcomes for two time periods (2015–2035 and 2035–2055) to holistically evaluate and identify the most suitable flood insurance market structure for a country: insurance penetration rate, incentivised risk reduction, magnitude of unaffordability of premiums and the premium cost for low-risk households due to risk sharing. The most appropriate market structure is the one that best manages the trade-offs between the modelled outcomes, given a range of public policy priorities.

We focus on flood insurance coverage for high-risk households because the policy debate commonly focuses on this group of potential high-risk policyholders(1-6). This group comprises policyholders who can be affected by the 1/100-year (yr) flood event in the absence of any flood protection infrastructure.

The approach is based on the combination of pre-existing approaches under a unified scenario-based framework. This stylised approach limits the current influence of parameter uncertainty in the conclusions drawn from the model until further regional information can be developed.

The DIFI model consists of several steps that are summarised below and explained in detail in SI2–SI5:

1. The expected annual flood loss and variance of losses is simulated at a 100 m × 100 m grid across Europe using an adaptation (described in SI2) of the European flood risk model developed by Feyen et al.(7) and Rojas et al.(8). Risk simulations are subsequently aggregated to NUTS 2 regions (see SI2).
2. The expected annual loss and the variance of losses for NUTS 2 regions are converted into household insurance premiums for the modelled market structures based on the flood insurance model presented in Paudel et al.(9) and Paudel et al.(10) and adapted in Hudson et al.(11) (see SI3). The six selected market structures are stylised versions of flood insurance market features, as distilled from extensive literature reviews (see SI8). Table 2 in the manuscript presents the stylised market structures.
3. The behaviour of households at risk of flooding is based on the concept of subjective expected utility(12) and the model presented in Hudson et al.(11) under a given stylised scenario of household flood risk perceptions for each flood insurance market structure. Household flood risk perceptions consist of two elements: subjective flood occurrence probabilities and subjective perceptions of the reduction in flood risk that can be achieved with flood-proofing measures. For each household at risk within a NUTS 2 region at risk of flooding, we model behaviour in the following manner:
    - 3.1. The subjective flood probability occurrence scenario is based on three sources of data: Botzen et al.(13), Botzen et al.(14) and the German Insurance Association (GDV)(15). Botzen et al.(13) and Botzen et al.(14) investigated and compared households' subjective flood occurrence probability and the objective flood occurrence probability. Subjective flood occurrences are complemented by perceived flood impacts based on a calibrated distribution from the data presented in GDV(15). The subjective flood occurrence scenario is combined with one of three different scenarios of individual perceptions of risk reduction from flood-proofing. These risk reduction perception scenarios are based on three empirical studies of households in flood-prone regions in the EU(5, 16, 17). Each of these studies conducted surveys of flood-prone regions to collect empirical information on the type of flood preparedness measures that each household has employed, on the basis of which a distribution of perceptions of risk reduction has been calibrated (see SI4.2). The final outcomes of this step are three combined flood risk perception scenarios.
    - 3.2. A household decides if it will employ a flood risk reduction measure based on a subjective cost–benefit analysis(11) and employs a measure if it is both economically desirable and affordable (see SI4.1). This step generates the baseline level of achieved risk reduction, which is used for judging the effectiveness of insurance incentives in stimulating the implementation of additional risk reduction measures (see SI4.2).

   - 3.3. The same household then decides if it will buy an insurance policy based on the market structure, discounts for the risk reduction measures, their subjective flood risk perceptions and the affordability of insurance premiums given the household's income (see SI4.1).
   - 3.4. If the household buys an insurance policy, it is eligible for a risk reduction incentive in the form of a premium discount from the insurer. The household will employ a risk reduction measure if the measure is cost effective with this incentive(11), and if it has not previously employed the risk reduction measure (see SI4.2). The potential discount offered by insurers is based on estimates provided by Hudson et al.(18). Hudson et al.(18) used propensity score matching to refine previous empirical estimates of the effectiveness of several household-level flood risk reduction measures in preventing damage.
4. After modelling the behaviour for each household across all NUTS 2 regions, the values of the following criteria are aggregated to the national level for each insurance market structure (for a 20-year period): the national mean insurance penetration rate, the magnitude of unaffordability, the cost for low-risk households due to the market structure's degree of risk sharing and the mean degree of incentivised risk reduction. This step is completed for all three combined flood risk perception scenarios, and the ensemble mean across the flood risk perception scenarios for the criteria is calculated.
5. The ensemble mean values of the criteria are then placed in a multi-criteria-style analysis to evaluate the preferred market structure through the following steps (see SI.5):
   - 5.1. The ensemble mean values are standardised across market structures within a country on a [0, 1] scale. The closer a standardised criterion value is to 1, the better the market structure performs on that criterion as compared to the other market structures.
   - 5.2. The standardised values are weighted and summed to produce a final overall score for each market structure within a country on a [0, 1] scale.
   - 5.3. The market structure within a country with the highest overall weighted score is deemed to be the most suitable market structure.

The modular nature of the framework allows the geographical scale of the model to be varied. However, the common data points required are as follows:

- An estimate of the annual expected loss per household, and the volatility of potential losses;
- An estimate of the subjective flood risk perception distribution for both occurrence probabilities and risk reduction efforts;
- Information on the income distribution in the areas studied; and
- The relative weights of the evaluation criteria.

SI2. Flood risk model

An existing coupled hydrological flood damage model (LISFLOOD), as presented in Feyen et al.(7) and Rojas et al.(8), is employed. Rather than using the underlying model itself, we utilise the impact estimates for monetary damage and the affected population. The monetary damage simulations are converted into average annual expected losses for households that live in an area with a flood probability of at least 1% in the absence of protection standards (the high-risk area).

The combined model estimates the household-level loss $[L(p)_{j,t}]$ from a flood with an exceedance probability (occurrence probability) of p in NUTS 2 region[6] j at time t given a certain level of protection (PS_j). $L(p)_{j,t}$ is an increasing function of hazard $[H(p)_{j,t}]$, exposure $(E_{j,t})$ and vulnerability $(V_{j,t})$, which is shared over households at risk $\left(N_{j,t}\right)$ as shown in Eq. (1). Equation (1) estimates the average flood damage per household from a given flood event. Kron(19) provides definitions for exposure, vulnerability and hazard: exposure is the value of assets that can be flooded, vulnerability is the degree to which assets are susceptible to being damaged and hazard is defined as the magnitude of a hydrological event. The underlying flood risk model combines each of the above components using spatially referenced data to value the damage caused by a flood of a given exceedance probability. A damage probability curve is fitted based on a power-law function[7] from several occurrence probabilities. Damage amounts for the following return periods are estimated: 1/2, 1/5, 1/10, 1/20, 1/50, 1/100, 1/250 and 1/500. A Monte Carlo simulation using these return periods produces an estimate of the annual expected flood loss per household and the variance of losses[8]. Flood risk is calculated at the NUTS 2 level by aggregating grid-level data.

$$L(p)_{j,t} = \frac{f\left(H(p)_{j,t}, E_{j,t}, V_{j,t}\right)}{N_{j,t}} | PS_j \tag{1}$$

The hazard element is defined as the modelled inundation extent and depth of a given flood event. The presence of protection standards (i.e. dikes) is accounted for in the hazard element of the flood risk model. A country that lacks protection standards would calculate risk over the probability range [0, 1]. Following Jongman et al.(20), the presence of protection standards truncates the upper bound from 1 to the flood probability that exceeds the protection standard (PS_j). For example, a protection standard of 1% indicates that only a flood event with an exceedance probability equal to or smaller than 1% will cause an impact. The assumption is that protection standards are fixed over time(8, 20-22). It implies that governments maintain a constant flood occurrence probability by altering protection infrastructure as required. The values of PS_j used are obtained from Jongman et al.(20) who provide an estimate of regional protection standards in Europe.

This study uses socioeconomic and climate change projections to estimate future values for exposure and hazard(20). Changes in the flood hazard over time were simulated using climate change projections based on the SRES A1 greenhouse gas emissions scenario, as produced by the Center for International Earth Science Information Network (CIESIN)[9]. The future value of exposed assets and population was estimated by rescaling impacts through the ratio of the future and baseline real GDP (for the value of future assets) or future and baseline population (for the number of individuals in the high-risk area)(20). Land use classifications are assumed to remain constant over time, which indicates that changes in exposure alter the value of land parcels. The impacts are rescaled according to the ensemble mean of the various Shared Socioeconomic Pathways (SSP) scenarios as provided by IIASA[10]. For Western Europe, there is not a large difference in the projected losses per household when rescaled using the SSP or SRES projections; by contrast, the SSP scenarios for Eastern Europe produce more realistic

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[6] A NUTS 2 region is an EU geo-spatial code based roughly on national administrative divisions. For instance, German NUTS 2 regions correspond to a *Regierungsbezirke*, while French regions correspond to *Région*. However, not all such regions are at risk of flooding. The population affected by flooding is also estimated through the risk model.

[7] A power law function takes the form: $L = \tau_1 + \tau_2 p^{\tau_3}$

[8] A Monte Carlo analysis was used in order to match the process used to estimate the flood insurance purchase decision of households (SI4.1).

[9] This exposure data is obtained from http://ciesin.columbia.edu/datasets/downscaled/

[10] https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=about

socioeconomic development pathways given observed current socioeconomic trends. The use of an SRES socioeconomic projection is examined in the sensitivity analysis (SI6.2).

Vulnerability is primarily accounted for by applying stage-damage curves that are used for converting flood inundation depths into monetary damage values$^{(23, 24)}$. Each land exposure class has a separate stage-damage curve implying a different relation between inundation depth and monetary loss. We focus on the land-use classes that correspond to residential areas. The use of household-level risk reduction measures (SI4) alters the slope of the stage-damage curve, which implies that lesser damage is suffered for a given flood inundation depth.

The values for $N_{j,t}$ are assessed by rescaling the estimated population affected by flooding by the average number of households per population based on Eq. (2)[11].

$$N_{j,t} = P_{j,t}\overline{\left(\frac{H}{P}\right)}_j , \tag{2}$$

where $P_{j,t}$ stands for national population within high-risk areas, and $\overline{\left(\frac{H}{P}\right)}_j$ denotes the average ratio of households to population within a country for the years 2000–2014. The estimate produced by Eq. (2) is a possible lower bound because many countries may experience a movement towards more single occupant homes due to aging populations. In effect, populations in flood prone areas change following the SSP scenarios. The distribution of populations between areas remains constant because there is not sufficient data for breaking down the relative changes in population at the NUTS 2 level for the scenarios studied. The effect of changing the ratio of $\overline{\left(\frac{H}{P}\right)}$ that drives insurance premiums, which is similar to changing the distribution of population to households, is studied in SI6.1.

SI3. Insurer sector model

The insurer element of the DIFI model consists of several components that are investigated for each country. The first element to be determined is how the base risk element of insurance premiums differs across market structures (SI3.1). Next, the potential behaviour of insurers must be considered. The main questions for insurers to consider pertain to the cost or profit loading factors that they will place on the risk element of an insurance premium (SI3.2) and the potential discounts that insurers will offer to households that employ risk reduction measures (SI3.3). Finally, as this study is concerned with high-risk households, we must account for the potential explicit or implicit subsidisation of high-risk households' insurance premiums through increasing insurance premiums for households with a low flood risk (SI3.4).

We assume that each country under investigation has an insurance market that is willing to provide, and capable of providing, flood insurance to consumers as long as the consumer pays the offered premium[12]. This paper only considers the insurers' underwriting business and not the possible investment decisions and their desire to engage in the flood insurance market. The consumers and insurance products are defined over the high-risk households. In all modelled insurance market structures, the insurance premium is calculated at the start of the year under investigation and is set at that value until the next year before considering household-level risk reduction. Only households that employ risk reduction measures can receive premium discounts equal to the average reduction in flood risk that these measures achieve. This assumption maintains a flow of insurance premiums that matches the expected annual loss on average.

We develop six stylised flood insurance market structures (M1–M6) (Table 2) by adapting the EU flood insurance market structures presented in Schwarze et al.$^{(25)}$ based on the collected information about the varying market structures across Europe (see SI8). Current flood insurance structures in European countries are assigned to M1–M3. These stylised market structures thereby capture the average

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[11] The data for population and household numbers is taken from official Eurostat data over 2000-2014, variables: tgs00096 and lfst_r_lfd2hh

[12] This is not always the case.

performances and structures for the market as a whole. Some deviation may emerge between the stylised assumptions and the occurrences in practice, even though they capture the core characteristics.

(M1) In *solidarity public structures*, all households must buy an insurance policy at a fixed price, regardless of objective flood risk and personal preferences. Governments cover part of the flood risk, and premiums are unconnected to risk.

(M2) The *voluntary private market* structure lacks this government coverage, allows households the free choice of whether to buy flood insurance and offers risk-based premiums.

(M3) The *semi-voluntary private market* is similar, except that mortgage conditions require comprehensive insurance coverage, resulting in a high market penetration rate. These conditions imply that damages to buildings are almost universally insured, whereas contents within a building are less often insured.

In addition to these three existing structures, we propose three new types of market structures (M4–M6) based on a public–private partnership (PPP) between the state and private insurers (see Table 2).

(M4) The *semi-voluntary PPP* is the semi-voluntary private market, except that it is supported by a not-for-profit public reinsurer that charges a reinsurance premium for reinsurance coverage. It connects flood insurance coverage to mortgages or other purchase requirements. Introducing a public non-profit and risk-neutral reinsurer for the extreme portion of risk will limit insurance premiums for households.

(M5) The *voluntary PPP* has no purchase requirements, in contrast to the semi-voluntary PPP, and it is also supported by a not-for-profit public reinsurer that charges a reinsurance premium for reinsurance coverage.

(M6) The *PPP market* is a compromise between (M4) and (M5). It connects insurance coverage with mortgage (or rental) conditions, and premiums are risk-based up to a threshold level at which the premium is capped. A capped premium is lower than the expected loss for high-risk households. To maintain insurer solvency, this shortfall is accounted for by placing a surcharge on the lower-risk households. The pool of high-risk households is also reinsured by a public reinsurer (in return for a reinsurance premium), which provides capital when losses exceed the expected loss.

SI3.1 Market structures

The base structure of insurance premiums across market structures is based on Hudson et al.(11), Paudel et al.(9) and Paudel et al.(10). The premium that insurers charge households differs across market structures, and it takes the form displayed in Eq. (3), where $\pi_{i,j,t,s}$ represents the premium charged to household i in NUTS 2 region j at time t under market structure s, with s taking the value 1 for the solidarity market structure, 2 for the PPP market, 3 for the voluntary market structure, 4 for the semi-voluntary structure, 5 and 6 are the fully and semi-voluntary structures with a PPP, respectively; ER_{DRR} is the discount (discussed in SI3.3) that insurers will provide depending on the level of household risk reduction as described in SI3.2; and $\bar{\pi}_{j,t,s}$ is the baseline average risk per household within a particular market structure for a given NUTS 2 region.

$$\pi_{i,j,t,s} = (1 - ER_{DRR})\bar{\pi}_{j,t,s} \tag{3}$$

SI3.1.1 Solidarity market

In this market, the expected national annual loss (rather than the high-risk annual loss) is equally shared across all households in a nation regardless of individual risk. This practice results in a high degree of risk sharing between households and limits concerns about affordability. The insurance premium for the solidarity market structure is shown in Eq. (4). In Eq. (4), $D_{j,t}(p)$ stands for the total value of the deductible that must be paid by households for a flood event with an occurrence probability of p. Paudel et al.(10) developed a model that estimates economically optimal deductible (reinsurance) levels for policyholders (insurers) and estimated an optimal deductible (reinsurance) level of about 15%.

Therefore, $D_{j,t}(p) = 0.15$. The insurance premium is calculated as the average expected annual damage that the insurer will compensate over the range of damaging floods [0, PS_c]. The solidarity market employs the subscript *c* rather than j, as premiums are only differentiated at the national level. Losses are shared over the entire nation regardless of the risk levels faced by individual households. This type of insurance market draws heavily from the markets in France and Belgium, where flood insurance coverage is a mandatory extension of household insurance policies.

$$\overline{\pi}_{c,t,1} = \frac{E\left(L_{c,t}(p) - D_{c,t}(p)\right)}{N_{c,t}} \tag{4}$$

SI3.1.2 Public–private market (PPP)

The premium for the PPP insurance market structure is presented in Eq. (5). Equation (5) introduces several additional terms: $\dot{\lambda}_{c,t}$, which is the cost-loading factor of the primary insurer; $\dddot{\lambda}_{c,t}$, which is the cost-loading factor of the public reinsurer (as defined in SI3.2) operating within country *c*; the superscript *RR,* indicating the risk ceded by the primary insurer to the reinsurance market; r, which is the risk aversion coefficient of the private insurers; $\sigma_{0<a<99.8}$, which is the volatility of flood damage within the range that is considered insurable⁽¹⁰⁾; $\overline{L}_{j,t}$ and $\overline{D}_{j,t}$, which are the modelled damage and deductible per high-risk household, respectively; and $CAP_{j,t}$, which is the maximum premium in region *j* at time *t* that insurers will provide through the formal cross-subsidisation between high- and low-risk households.

$$\overline{\pi}_{j,t,2} = \min\begin{cases} (1+\dot{\lambda}_{c,t})\left(E\left(\overline{L_{j,t}}(p) - \overline{D_{j,t}}(p)\right) + r * \sigma_{0<a<99.8}\right) + \left(1+\dddot{\lambda}_{c,t}\right)\left(E\left(\overline{L_{j,t}^{RR}}(p) - \overline{D_{j,t}^{RR}}(p)\right) + r * \sigma_{0<a<99.8}^{RR}\right) \\ (1+\dddot{\lambda}_{c,t})CAP_{j,t} \end{cases} \tag{5}$$

In the PPP market, households are offered premiums that are more strongly connected to the risk faced by high-risk households than in the solidarity market structure. However, these premiums are less strongly connected to risk when compared to private market structures. The reason is that the premium is allowed to increase with risk until a certain point is reached, above which the premium is capped. The capped premium brings aspects of solidarity into this market structure. The first element of Eq. (5) is the risk-based premium, whereas the second element is the capped insurance premium.

The value for $CAP_{j,t}$ is fixed for high-risk households within region j in a similar manner to the UK's Flood Re insurance pool for high-risk households. The Flood Re premium is set per household, with the most common potential cap being equal to £280⁽²⁶⁾, which is approximately €311, or 1.8% of the 2014 median British household income according to Eurostat[13]. A similar capped premium is applied by setting the capped premium equal to 1.8% of the estimated regional median income. Over time, the cap increases at the same rate as the change in the total value of exposure.

SI3.1.3 Voluntary or semi-voluntary market

The structure of the premium under the voluntary or semi-voluntary market structure is shown in Eq. (6):

$$\bar{\pi}_{j,t,3} = (1+\dot{\lambda}_{c,t})\left(E\left(\overline{L_{j,t}}(p) - \overline{D_{j,t}}(p)\right) + r * \sigma_{0<a<99.8}\right) + (1+\ddot{\lambda}_{c,t})\left(E\left(\overline{L_{j,t}^{RR}}(p) - \overline{D_{j,t}^{RR}}(p)\right) + r * \sigma_{0<a<99.8}^{RR}\right) \tag{6}$$

The premiums are not cross-subsidised; therefore, low- and high-risk households are offered a premium that is risk-based, implying a full risk signal. The voluntary market structure can be altered by the introduction of a public–private sector partnership by replacing $\ddot{\lambda}_{c,t}$ with $\dddot{\lambda}_{c,t}$.

SI3.2 Competition and loading factors

In several structures, the insurance industry charges a loading factor ($\lambda_{c,t}$), as indicated in the previous sections. Equation (8) shows that $\lambda_{c,t}$ can be further subdivided into three elements: $C_{c,t}$ is the cost of providing an insurance policy, $\dot{P}L_{c,t}$ is the profit loading for primary insurers and $\ddot{P}L_{c,t}$ is the profit

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[13] Eurostat variable: ilc_di03

loading for private reinsurance companies. We allow the profit loading factor to differ across layers of insurance, while $C_{c,t}$ is constant across layers.

$$\lambda_{j,t} = \begin{cases} \lambda_{j,t} = C_{c,t} + \dot{P}L_{j,t} & if\ primary\ insurer \\ \ddot{\lambda}_{j,t} = C_{c,t} + \ddot{P}L_{j,t} & if\ private\ reinsurer \\ \dddot{\lambda}_{j,t} = C_{c,t} & if\ public\ reinsurer \end{cases} \tag{8}$$

Competition in primary insurance markets is assumed to follow Bertrand competition, whereby insurers compete on prices or loading factors⁽²⁷⁾. The default assumption is that $\dot{P}L_{c,t}$ is set equal to 0 because with homogenous insurers, Bertrand competition results in a perfectly competitive market. We assume that reinsurance markets are dominated by a smaller number of firms, allowing for $\ddot{P}L_{c,t} = 0.5^{(28)}$.

The value of $C_{c,t}$ is displayed in Eq. (9), in which the cost of providing insurance is a fixed percentage of the insurance premium.

$$C_{c,t} = \frac{Operating\ costs_{c,t}}{Total\ premiums_{c,t}} \tag{9}$$

To arrive at a cost function for each national insurance industry, we obtain data from the OECD[14] insurance statistics database regarding the total value of gross premiums collected by the insurance industry and the total gross operating expenses for the years 2004–2014 for non-life insurance.

Equation (10) is the econometric model used for estimating Eq. (9). Equation (10) is a multi-level hierarchical model, where we allow the parameters of interest to vary over countries. A hierarchical model is estimated; as such, a model uses the pan-national sample for estimating country-specific parameters. This aspect is important; otherwise, each country would have 10 observations. In Eq. (10), β_k are estimated parameters that are constant across countries, $\dot{\mu}_{c,k}$ are estimated random effect parameters that vary across countries, $T_{c,t}$ is the time trend, *ln* represents the natural logarithm of the cost ratio to prevent the estimated values of $\mathrm{C}_{\mathrm{c,t}}$ from becoming negative and $\dot{e}_{j,t}$ is the error term:

$$\mathrm{Ln}(\mathrm{C}_{\mathrm{c,t}}) = \beta_1 + \dot{\mu}_{\mathrm{c},1} + (\beta_2 + \dot{\mu}_{\mathrm{c},2})\mathrm{T}_{c,t} + \dot{\mathrm{e}}_{\mathrm{c,t}} \tag{10}$$

A country-specific equation is the sum of the two sets of parameters. The estimated surcharges per country are presented in Table SI1. Table SI1 shows that across the EU countries, a long-run trend of a falling ratio of operating costs to premiums generally occurs, indicating increasing efficiency in the industry, which corresponds to an approximately 5% fall every year, on average, across the countries. However, the standard deviations of the random effect estimate for the time trend are relatively wide, indicating that national contexts are quite different. The time trend results in two roughly equally sized groups of countries: those where cost loadings are increasing and those where cost loadings are falling. The group with falling costs tends towards a cost loading factor of about 2% of premiums by 2055, whereas the group with increasing costs tends towards a loading factor of roughly 25% by 2055. National loading factors are assumed to equal the sample average if national data are missing.

SI3.3. Insurance incentives for risk reduction (premium discounts)

Two risk reduction measures are focused upon: wet flood-proofing and dry flood-proofing buildings. Wet flood-proofing measures aim to limit the damage once water has entered a building, whereas dry flood-proofing aims to limit damage by preventing water from entering a building.

Hudson et al.⁽¹¹⁾ developed an effectiveness indicator for wet and dry flood-proofing, which is the ratio of flood damage prevented to average flood damage suffered. The effectiveness indicator for wet flood-proofing is valued at 0.246 (confidence interval: 0.191–0.301)[15], with an estimated investment cost of €2,389 per building (with a range of €800–€7,250). The effectiveness indicator for dry flood-proofing is valued at 0.128 (confidence interval: 0.082–0.174), with an estimated investment cost of €471 per

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[14] OECD Stats (database), doi: 10.1787/ins-data-en

[15] This was calculated by assuming a normal distribution and using the variance of the effectiveness of dry or wet flood-proofing measures from Hudson et al. (18) and the variance of the risk data from Kreibich et al. (17). The confidence interval is calculated as $ER \pm 1.96\sqrt{Var\left(\frac{Damage\ Prevented}{Damage\ Suffered}\right)}$.

building (with a range of €265–€845)[16]. The maximum degree of risk reduction is 37.4% if households employ both wet and dry flood-proofing measures. Therefore, the possible premium discounts are shown in Eq. (11) as the percentage by which the initially offered premium is lowered. The total discount of 37.4% is similar in size to the risk modelling results of Poussin et al.(29), whose methodology estimated that wet and dry flood-proofing retrofits of buildings can reduce flood risk by 40–45%.

$$ER_{DRR} = \begin{cases} 0.128 & if \quad DRR = dry\, flood - proofing \\ 0.246 & if \quad DRR = wet\, flood - proofing \\ 0.37.4 & if \quad DRR = both\, flood - proofing \end{cases} \tag{11}$$

The households that implement these measures face lower premiums. The set of possible discounts assumes that the effectiveness of one measure does not alter the effectiveness of the other because the measures focus on different aspects of protection.

SI3.4. Cost for low-risk households due to the level of risk sharing within a market structure

The insurance market structure can also place an additional cost on the households with low flood risk through the introduction of an explicit premium cross-subsidy between households. Such a subsidy requires some of the cost for households with high flood risk to be borne by households with low flood risk. This cost is viewed as a societal cost, as it forces low-risk households to pay larger insurance premiums for no return of insurance coverage(30). Low-risk households are defined as those with a flood probability that is lower than 1% per year (in the absence of protection standards). The cost for low-risk households, in total across the low-risk population, is presented in Eq. (12). It is measured as the difference between the premiums that the insurance company collects from the high flood-risk households compared to the total expected damage to high-risk households in terms of the net present value (NPV). Annual values are discounted at a rate of 3.5%.

$$Cost_{low\, risk\, households_{j,t}} = \Sigma_0^{20} \left(\frac{1}{1+0.035}\right)^t \left(\Sigma_i E\left(\bar{L}_{i,j,t}(p) - \bar{D}_{i,j,t}(p)\right) - \pi_{i,j,t,s}\right) \tag{12}$$

In other words, the cost for low-risk households is the NPV of the subsidy that high-risk households receive from lower risk households. This subsidy is provided through a surcharge on the insurance policies of the low-risk households, for which they gain no direct benefit.

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[16] The cost estimate of the measure is based on Poussin et al (29)).

SI4. Model of household insurance demand and risk reduction behaviour

The consumer element of the DIFI model is household behaviour that consists of two components. The first one considers whether a household will or will not buy insurance based on its decision-making process, which follows subjective expected utility theory(12) in SI4.1. Once a household has decided to buy insurance, it is exposed to an external incentive to employ risk reduction measures. Therefore, the risk reduction decision process must be considered (SI4.2).

SI4.1 Flood insurance demand

Based on a review of the available literature (see SI8), we posit assumptions regarding the flood insurance penetration rate in non-voluntary flood insurance markets. The solidarity market structure is assumed to have a penetration rate of 100% due to the formal legal mandate to buy flood coverage (see the examples of France and Spain)[17]. The penetration rate of the semi-voluntary market is assumed to be 75%, which is based on the overlap between the estimates of penetration rates for the UK, Sweden, Ireland and Hungary gathered from the references listed in SI8.

The assumed penetration rate for the PPP market is 85%, as PPP premiums are lower, thus inducing more low-income households or non-mortgaged residents to buy insurance. This estimate is a compromise between the penetration rates of the semi-voluntary and full solidarity markets. The semi-voluntary and PPP markets have a lower than 100% coverage rate even with a purchase requirement. The reasons are that building contents are less often insured[18] and many low-income households may not insure(26). Moreover, flood coverage in these markets is an informal requirement (i.e. connected to the purchase of a mortgage) rather than a formal requirement (i.e. a legal requirement to buy insurance); thus, not all households buy insurance. In these cases, we assume that the enforcement of purchase requirements is effective.

The household behaviour model consists of two elements based on stylised scenarios. The first element applies only to the voluntary market structure, in which households have the choice of buying insurance. The assumption is that households will buy insurance if it is both utility-maximising and affordable in a subjective expected utility framework(12), which is a standard economic model of individual decision making under risk. In Eq. (13), the new terms are $W_{i,j,t}$, which is the estimated wealth of a household in region j at time t[19], and α_i, which is the risk aversion of a household and is set at α_i=1, resulting in a log utility function. Subjective flood perceptions are introduced by assuming that households consider losses over the probability range $[0,\widetilde{PS}_{i,j}]$, where $\widetilde{PS}_{i,j} = \vartheta_{i,j}PS_j$; and $\gamma_{i,j}$, which is the perceived flood impact.

In Eq. (13), the first element calculates the subjective expected utility of not being insured, that is, uncompensated flood losses. The second element presents the subjective expected utility of being insured. In that case, the agent can only suffer a loss equal to the insurance deductible.

$$E(U) = \begin{cases} E\left(U_{1,i,j,t,s}\right) = \int_0^{p=\widetilde{PS}_{i,j}} p\ln\left(W_{i,j,t} - \gamma_{i,j}L_{i,j,t}(p)\right) dp \\ E\left(U_{2,i,j,t,s}\right) = \int_0^{p=\widetilde{PS}_{i,j}} p\ln\left(W_{i,j,t} - 0.15\gamma_{i,j}L_{i,j,t}(p) - \pi_{i,j,t,s}\right) dp \end{cases} \tag{13}$$

A potential policyholder will select the element of Eq. (13), which provides the highest expected utility, subject to meeting the budget constraint. An important input for calculating Eq. (13) is a distribution of individual flood perceptions. To generate a probability density function, information about subjective occurrence probabilities is required for $\vartheta_{i,j}$. The data used to generate this distribution are obtained from Botzen et al.(13, 14). These studies investigated how the households' perceptions of flood

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[17] Romania is the exception in this grouping with a penetration rate of less than 20%. However, it displays the rest of the features of this market.

[18] The underlying risk model does not strongly differentiate between building and contents damage, which is why we do not explicitly distinguish between the possible wish to by an insurance policy against these separate damage categories.

[19] Wealth is estimated by assuming it is a fixed proportion of income as indicated by: http://ec.europa.eu/eurostat/documents/3433488/5565228/KS-SF-10-033-EN.PDF/9b1042cd-4f2d-4984-9afe-aef8e5be3a5c?version=1.0; missing observations are set equal the sample average of 2.27 times income. Assuming a fixed ratio may underestimate the wealth of some households, thereby indicating that flood losses are more important than they are for a given level of wealth. This, however, produces an optimistic estimate of insurance penetration rates.

probabilities compared with objective flooding probabilities. Results indicate that the data follow a generalised Pareto distribution[20], as judged by Bayesian information criteria.

The Probability Distribution Function (PDF) of the generalised Pareto distribution, $[f\left(\vartheta_{i,j}\middle|k,\sigma,\theta\right)]$, is given by Eq. (14), and the calibrated parameters are presented in Table SI3. The parameter θ can be interpreted as a threshold value. If $k > 0$, then $\vartheta_{i,j}$ can only take values such that $\vartheta_{i,j} \geq \theta$.

$$f\left(\vartheta_{i,j}\middle|k,\sigma,\theta\right) = \left(\frac{1}{\sigma}\right)\left(1 + k\frac{\vartheta-\theta}{\sigma}\right)^{-\frac{1}{k}} \tag{14}$$

The fitted generalised Pareto distributions must be calibrated to national contexts. This step is undertaken by following the approach developed by Hudson et al.$^{(11)}$, in which deviations in subjective flood occurrence probabilities are related to the protection standards currently in place. We assume that the required generalised Pareto distribution can be linearly interpolated based on the distribution estimated from the data presented in Botzen et al.$^{(13,\,14)}$. In most cases, only the top 3% of values of the above distributions create a probability range outside of [0,1]. To correct this aspect, we fit the above distributions and draw 10,000 values over the domain $[0,\ 1/PS_j]$. This amendment is made because $\widetilde{PS}_{i,j}$ must have a maximum value of 1 to match the exceedance-probability curve.

A similar distribution must be calibrated for $\gamma_{i,j}$. A generalised Pareto distribution is selected and calibrated based on data for Germany from GDV$^{(15)}$. Germany was selected for this case because it provides the most detailed information in Europe for a situation of voluntary flood insurance purchase. A similar level of detail regarding flood insurance specifically is unavailable for other voluntary markets across Europe.

The GDV$^{(15)}$ states that on average, the flood insurance penetration rate for German households in 2013 was 33% for buildings and 19% for building contents. The generalised Pareto distribution is calibrated such that the DIFI model produces an average penetration rate of 26% for Germany in 2015 under the private voluntary market structure. The calibrated distribution is then equally applied to other countries within the sample due to problems of data availability or the presence of a counterfactual situation (for example, France). The effect of this parameter is examined in SI6.1.3. Germany was selected for this example as it is one of the few voluntary markets where reliable information on the penetration rate is known.

These calibrated risk perception distributions can be considered as a type of stylised scenario for these values in the absence of more detailed information. Therefore, as this scenario is stylised, the results may differ from actual outcomes, but the current focus on comparative outcomes mitigates this uncertainty.

The budget constraint for Eq. (13) is considered to assess the affordability of the insurance (given possible expenditure on risk reduction measures). If the entire or a proportion of the insurance premium is deemed to be unaffordable, then the household will not buy the insurance policy. The reason is that although an insurance policy may be beneficial in the long run, a household is unlikely to buy it when it is currently unaffordable. Moreover, this aspect captures the tendency of higher income households to be willing to pay more for flood insurance$^{(31)}$. This tendency may differ from other insurance models for durable goods (e.g. homes or cars)[21]. Additionally, due to the low-probability/high-impact nature of flood events, various behavioural heuristics cause individuals exposed to flood risk to act in very different ways compared to higher probability events (i.e. house fires). This is accounted for by allowing for deviations between perceived and objective risk.

Affordability is measured based on a method constructed by Hudson et al.$^{(11)}$, which is derived from equity concerns, and it may be the most robust of those currently presented regarding flood insurance$^{(32)}$.

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[20] The approach taken follows Hudson et al. (11) whereby the desirability of the following distributions was tested against one another: Exponential, Extreme Value, Generalized Extreme Value, Generalized Pareto, Logistic, Normal, T-location scale.

[21] For example, damage is estimated based on land-use classes and as such estimates a total loss, rather than losses from the policyholder's building or its contents.

This definition is that an item of expenditure is unaffordable for a household if the money to be spent is larger than the household's poverty-adjusted disposable income (i.e. disposable income above the relative poverty line). The constraint presented in Eq. (15) shows this mathematically as follows: $Income_{i,j,t}$ being the household's income and the poverty line being taken as the national poverty line (i.e. 60% of national median income). The magnitude of unaffordability for insurance premiums is estimated by the total sum of the unaffordable portion of an insurance premium within a given year.

The expression in Eq. (15) summarises the households' decision process. Households will buy insurance if it is both subjectively expected utility-maximising and affordable.

$$U = \begin{cases} insure & if \quad E(U)_{1,i,j,t,s} < E(U)_{2,i,j,t,s} \quad s.t. \pi_{i,j,t,s} \leq Income_{i,j,t} - Poverty\ Line_{c,t} \\ not\ insure & if \quad E(U)_{1,i,j,t,s} \geq E(U)_{2,i,j,t,s} \quad or \quad \pi_{i,j,t,s} > Income_{i,j,t} - Poverty\ Line_{c,t} \end{cases} \tag{15}$$

Income for each household within every NUTS 2 region is drawn from a log-normal distribution, as is common(33-35). Wealth is assumed to be a fixed ratio of income obtained from Eurostat. The log-normal distribution is calibrated to NUTS 2 data on mean and median income levels[22]. Incomes and therefore wealth grow at the same rate as overall exposure, which can be interpreted as higher house prices and greater amounts of durable goods within a building, among others.

SI4.2 Employment of risk reduction measures

The second component of household behaviour that is modelled is the decision to invest in flood risk reduction measures. The approach adopted is based on Hudson et al.(11), which we extend here to account for budget constraints. We assume that policyholders make investment decisions on the basis of costs and benefits; meanwhile, the perceived benefits of mitigation can diverge from actual benefits due to the over- or underestimation of flood risk or the benefits of risk reduction measures[23]. The reason is that although a measure may be cost effective in the long run, a household is unlikely to employ such a measure when it is currently unaffordable.

Households can consider investing in each measure separately. Equation (16) shows that the benefits of investing in one of the three choices for flood-proofing ($\omega_{i,j,t,DRR}$) differ, and the choices are dependent on whether households base their decision on their perceived benefits or an insurance incentive in the form of a premium discount. $\mathrm{ER}_{\mathrm{DRR}}$ is the discount that households receive if a risk reduction measure is employed.

$$Benefits = \begin{cases} \omega_{i,j,t,s,DRR}^{Incentive} = ER_{DRR}\pi_{j,t,s} \\ \omega_{i,j,t,DRR}^{Subjective} = \varphi_{i,j} ER_{DRR} \frac{\int_0^{PS_j} pL(p)_{j,t}dp}{N_{j,t}}, \end{cases} \tag{16}$$

The households are assumed to have the following choice set of risk reduction measures (dry flood-proofing, wet flood-proofing, dry and wet flood-proofing) matching the set of possible premium discounts. The first element of Eq. (16) is the case when the insurer offers financial incentives (premium discounts), whereas the second element is the case where households base their investment decision on their perceived benefits. The perceived benefits are based on the household's share of the expected regional loss, which are converted into subjective benefits via φ_i. The variable φ_i is a random draw for each household from the overall φ distribution of risk reduction perceptions[24]. This variable accounts for the possible misperceptions of the flood probability, the expected flood loss and the potential effectiveness of the risk reduction measure. The variable $\varphi_{i,j}$ can take values over $[\underline{\varphi}(\geq 0), \infty]$. For instance, if $\varphi_{i,j} = 0$, then $\omega_{i,j,t}^{subjective} = 0$, the household sees no benefit from these measures; if $\varphi_{i,j} = 1$, the household's subjective risk reduction benefits equal the objective benefits; if $\varphi_{i,j} > 1$ benefits are overestimated; and if $1 > \varphi_{i,j}$ the benefits are underestimated.

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[22] The log-normal distribution only has two key parameters to be estimated, which are contained in the function for the mean and median values that can be found in Eurostat variables: nama_10r_2hhinc and nasa_10_ki

[23] Due to the data sources used it is impossible to disentangle separate sources of over- or underestimation.

[24] It is assumed that the subjective risk perceptions over DRR and flood occurrence probabilities are independent. It may, however, be the case that the two perceptions are correlated, but there is currently no study that has estimated the relationship between the various elements of risk perception.

Once the potential benefits in each period have been calculated, the household will make the cost-effectiveness calculation in Eq. (17), using the higher value benefit in Eq. (16). This step can be interpreted in the following manner: If a household underestimates the benefits from risk-reducing measures, then the decision to invest in mitigation is determined by the premium discount. Households that have subjective benefits of mitigation that are larger than the premium discount base their decision to mitigate on their subjective risk reduction beliefs. In other words, those households that overestimate the benefits of risk reduction will employ risk-reducing measures even if these measures are not objectively cost effective. These households have an intrinsic motivation to implement risk reduction measures, which proves to be an important part of the decision-making process(36).

$$\omega^{*}_{i,j,t} = \begin{cases} \omega^{Incentive}_{i,j,t,DRR} & if \ \omega^{Incentive}_{i,j,t,DRR} > \omega^{Subjective}_{i,j,t,DRR} \\ \omega^{Subjective}_{i,j,t,DRR} & if \ \omega^{Incentive}_{i,j,t,DRR} \leq \omega^{Subjective}_{i,j,t,DRR} \end{cases} \tag{17}$$

Once the benefit of mitigation in a time period has been decided upon, the overall investment decision framework is presented in Eq. (18). In Eq. (18), a household will decide to invest in a particular risk reduction measure if the discounted benefits over 20 years are larger than the upfront investment costs, IC_{DRR}. Discrete time discounting is used where the discount rate is given by δ.

$$uptake = \begin{cases} Yes \quad if \sum_0^{20} \left(\frac{1}{1+\delta}\right)^t \omega^{*}_{i,j,t} - IC_{DRR} \geq 0 \quad \& \quad \mathrm{IC_{DRR}} < \mathrm{Income_{i,j,t}} - \mathrm{Poverty\ Line} - \pi_{\mathrm{i,j,t}} \\ No \qquad\qquad\qquad if \sum_0^{20} \left(\frac{1}{1+\delta}\right)^t \omega^{*}_{i,j,t} - IC_{DRR} < 0 \end{cases} \tag{18}$$

$$IC_{DRR} = \begin{cases} €471 & if \quad DRR = dry\ flood - proofing \\ €2389 & if \quad DRR = wet\ flood - proofing \\ €2860 & if \quad DRR = both\ flood - proofing \end{cases}$$

δ is fixed at 3.5%. Households will only consider benefits over a 20-year period(37). This can be viewed either as the assumed lifespan of the measures or as myopia.

We follow the approach adopted in Hudson et al. (11), who calibrate the generalised Pareto distributions of subjective risk reduction perceptions based on the data about the implementation of flood preparedness measures by households in flood-prone areas(5, 16, 17). The calibration of the distribution of baseline risk reduction perceptions is based on the average risk faced and flood-proofing employment rate in the NUTS 2 regions covered in these studies. The parameters of the calibrated distribution are then assumed to be fixed and are applied to the separate NUTS 2 regions using the risk for that specific region.

In particular, the distribution is calibrated in a way where $\omega^{Subjective}_{i,j,t}$ results in cost-effective employment for a known proportion of the households at risk of flooding. The coefficient $\omega^{Subjective}_{i,j,t}$ pertains to the objective benefits rescaled by a draw from the risk reduction perceptions distribution. Therefore, the draw where the subjective benefits are to equal the measures investment costs (denoted as $\varphi_j{}^{*}$) determines the percentage of households that implement a particular measure. For example, if the value of $\varphi_j{}^{*}$ corresponds to the 90th quantile of the distribution, then the measure is cost effective for 10% of the households. Formally, the required value of φ^{*} is calculated using the following equation:

$$\varphi_j{}^{*} = \frac{IC_{DRR}}{ER_{DRR} \sum_0^{20} \left(\frac{1}{1+\delta}\right)^t \left(\frac{\int_0^{PS_j} pL(p)_{j,t} dp}{N_{j,t}} \right)} \tag{19}$$

The next step is to calibrate the parameters of the distribution in a way where φ^{*} corresponds to the value of the target quantile. Each risk reduction measure has a separate risk reduction perception distribution. The uncertainty of these distributions is reflected by calculating three of such distributions based on the survey data employed(5, 16, 17). These three estimates are interpreted as three different stylised scenarios of risk reduction perceptions; the resulting parameters are presented in Table SI3. The calibrated distributions indicate that the majority of households underestimate the overall benefits from dry or wet flood-proofing measures. The results may differ from actual outcomes at a particular location because of the use of stylised scenarios, but our focus on comparative outcomes between insurance market structures mitigates this uncertainty.

SI5. Multi-criteria analysis

The multi-criteria analysis (MCA) evaluation framework is based on the following key evaluation criteria: the mean national insurance penetration rate, the mean incentivised risk reduction, the NPV of magnitude of unaffordability, and the NPV of the cost that risk sharing between low- and high-risk households place on low-risk households. The values estimated in step 4 of the DIFI model are aggregated over time by generating the NPVs of the indicators for the periods 2015–2035 and 2035–2055. The insurance penetration rate is not converted into an NPV, but it is the average penetration rate over the period. The MCA is conducted at the national rather than the NUTS 2 level. Finally, the criterion values are aggregated over the three flood risk perception scenarios by using the average criterion value across the three scenarios.

Once the DIFI model output has been aggregated across flood risk perception scenarios at the national level, the criteria are standardised within a country and a weighted sum is produced. The weighted sum provides a single aggregated holistic score across the four criteria for each investigated national market structure within a country. The penetration rate and incentivised risk reduction are deemed to be benefits, whereas unaffordability and the cost for low-risk households are considered to be costs. This follows the public debate regarding the manner of conducting flood risk management.

The evaluation criteria are standardised and ranked following Eq. (21). ${S^1}_{c,s}$ is the score for market structure *s* in country *c* for the first period (or the second if ${S^2}_{c,s}$). The values for each indicator are standardised, as standardisation allows the variables to have a common metric and to be weighted according to perceived importance[25]. The standardisation process bounds score values by 0 and 1.

$$ {S^1}_{c,s} = \frac{\sum_{n=1}^{n=11}\sum_{m=1}^{m=4}\omega_m^n MCA_{j,t,s}}{11}, \quad where\ MCA_{m,j,t,s} = \begin{cases} \frac{A_{c,s}^1 - A_{c,s}^{1,Min}}{A_{c,s}^{1,Max} - A_{c,s}^{1,Min}} & if\ a\ benefit \\ 1 - \frac{A_{m,j,t,s}^1 - A_{m,j,t,s}^{1,Min}}{A_{c,s}^{1,Max} - A_{c,s}^{1,Min}} & if\ a\ cost \end{cases} \tag{21} $$

The possible choices for $\{\omega_m^n\}$ can alter the overall attractiveness of the various market structures for each country. To account for this potential effect, multiple sets of weights are used: (a) equal weights, where ω=1/4; (b) one element is weighted at ω=2/5 and the remaining two elements at ω=1/5 (with an alternating element with the double weight); and (c) two elements are weighted at ω=3/10 and the remaining elements at ω=1/5 (with alternating elements with the higher weight). There are 11 unique combinations of weights. These weights have been set by expert judgement to model outcomes under a range of potential public policy objectives. Moreover, the use of a wide range of weights allows for the investigation of whether a desirable market structure is most commonly highly scored across different main objectives.

The overall MCA score is quite likely to be sensitive to changes in the weights used. Furthermore, due to the lack of clear guidance from stakeholders to set weights at the European level, the ranking of insurance market structures is based on the mean aggregated score across the various sets of weights. We leave it to future research to determine the weights that are applicable to specific locations to better tailor the presented framework.

SI6. Sensitivity analysis

This section examines the sensitivity of our main results to a variety of important assumptions made in the DIFI model.

SI6.1 Uncertainty in risk and insurance premium estimates

An important source of uncertainty in this study is the estimated insurance premium, as the value of the premium is a major driving force behind the market rankings. Therefore, we examine the sensitivity of our main results to two sources of uncertainty in the premium, namely (1) uncertainty of the underlying aggregate risk estimate and (2) uncertainty of the number of households in a high-risk flood zone at a

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[25] While the mean score is presented in eq. (21) as the final indicator, using the median score does not produce noticeable differences.

certain point in time. It should be realised that the effects of including cost and profit loadings emanate from the underlying risk estimate, which is why the risk estimate is central to this sensitivity analysis.

The influence of uncertainty on the underlying risk estimate is examined by estimating the 95% confidence interval around the estimated probability exceedance curves used to calculate the expected annual damage. The upper and lower bounds of the damage estimates result in the estimated premiums being, on average, 4% higher or lower, respectively, across the EU countries over the entire period. Countries located in Western Europe are closer to a change of 1%, whereas those countries in Eastern Europe are closer to a change of 5%. The second source of uncertainty in premiums is the fact that the number of households is different per market structure. The solidarity market structure uses official Eurostat estimates for the number of households within a country and, thus, has little uncertainty. The remaining market structures require an estimation of the number of households in an area with high flood risk. The uncertainty in the number of households is measured by constructing a 95% confidence interval around the ratio of households to overall population. Using the upper limit (a smaller number of households) of this ratio increases the modelled premiums, whereas using the lower limit (a larger number of households) lowers average premiums. The effect of the uncertainty in the number of households has a larger effect on premiums than did the estimates of the risk. Nevertheless, taking these sources of uncertainty into account (individually) results in the PPP and semi-voluntary market features remaining the optimal market structure for most countries considered. The only noticeable difference is that under the lower risk bounds for the period 2035–2055, the PPP market is the optimal market in slightly fewer countries.

However, certain elements of the risk model cannot be specifically tested. For example, there remains a certain degree of uncertainty in the hydrological model being used at a large rather than a catchment scale, which introduces ambiguities in the estimates of future risk. This aspect has been noted in Rojas et al.(8). However, evaluating these sources of uncertainty is beyond the scope of this paper. Nevertheless, several studies such as Jongman et al.(20) have used a similar large-scale modelling approach to model flood risk at the European or global scale(21, 22, 38). Although climate change-induced changes to flood risks are important, a major driver of flood risk is modification in exposure, which is tested in the next sub-section.

SI6.2 Different flood risk scenarios

Instead of the current SSP scenarios of economic and population growth, the A1 climate projection can be combined with the SRES scenarios. Including the SRES scenarios produces a higher level of flood risk than the ensemble SSP scenarios we used for our baseline results; in particular, flood risk is up to 17 times higher due to economic development alone under the SRES scenarios. The main influence of using the higher flood risk projections based on SRES is that the PPP market becomes optimal for almost all countries because of its capacity to provide strong risk reduction incentives. This strengthens our baseline findings about the desirability of the PPP market.

SI6.3 Alternate construction of the insurance premium discount

Our initial analysis assumed that any risk reduction measure employed would lower the premium offered by the insurance sector. However, in the PPP and solidarity markets, the premium offered to households does not fully reflect their risk. Therefore, an alternative premium discount for risk reduction could be that premiums are only lowered if the policyholder lowers its total risk to a level below the capped premium. In effect, altering this assumption removes the household-level reward for risk reduction and prevents the employment of additional risk reduction measures in the PPP market structure. Altering this assumption renders the semi-voluntary market optimal for most countries. However, as mentioned in the main part of the paper, the semi-voluntary and PPP market structures have relatively similar features overall.

SI6.4 Using a single national pool of high-risk households rather than regional differentiation

Instead of basing the model on separate insurance premiums at the NUTS 2 level based on Hudson et al.(11), it can be based on a single pool of all NUTS 2 regions at the national level. This change would increase the degree of solidarity between households within the high-risk flood-plain. The main result of this alteration is that the semi-voluntary structure (PPP) becomes more often the optimal structure in the first period. However, the results in the second period are quite consistent between using separate regional pools or a single national pool. Overall, this change in geographical detail can result in a slightly different ranking for some countries, but the major conclusions regarding the most desirable market features remain the same.

SI6.5 Alternative assumptions about the costs and effectiveness of risk reduction measures

In this section, we examine the sensitivity of our main results to different assumptions about the costs and effectiveness of risk reduction measures, which can affect the estimated employment of these measures by households and the incentivised risk reduction by insurance. This step is done by running the model with the upper and low bounds of the cost estimates for both dry and wet flood-proofing reported in SI3.2. These results indicate that deviating from the baseline cost estimates does not change the impact of the risk reduction incentives for the solidarity insurance market structure. The reason is that the NPV of the premium discounts is too small, regardless of the costs, to influence decisions to take these measures. The results for the voluntary market structures and the PPP market structure imply that using the lower bound of the cost estimates increases the average amount of risk reduction occurring, whereas using the higher bound of costs lowers the total risk reduction. However, the overall ranking of insurance market structures is robust to using the upper cost estimate.

Apart from flood-proofing costs, there is the possibility that when a household employs both dry and wet flood-proofing measures, the two can interact with each other and reduce the total effectiveness of these measures. This in turn can limit the incentive to take both measures. The two measures are in effect sequential, in that dry flood-proofing aims at preventing water from entering a building and then wet flood-proofing mitigates the damage of water that still enters. In this sensitivity test, the assumption is that dry flood-proofing remains as effective as stated above, whereas the effectiveness of wet flood-proofing is reduced to 21%, to take into account that it offers less protection after dry flood-proofing is implemented. The results signify that this change has no noticeable influence on flood-proofing decisions.

SI6.6 Alternative assumptions on the utility function determining flood insurance demand

SI6.6.1 Alternate decision theory

There is a debate in the literature regarding how households behave when faced with low-probability/high-impact events and the behavioural heuristics involved(39). A range of behavioural rules have been proposed as alternatives to the subjective expected utility theory used for modelling individual flood insurance purchases for our main results. We investigate how sensitive our main findings are to using a different behavioural decision rule, namely prospect theory, which is the primary alternative theory that has been proposed to model individual decision making under low-probability/high-impact risk situations(13).

The utility function of prospect theory deviates from that of standard expected utility theory in that losses or gains are valued as deviations from a reference level of wealth. Additionally, prospect theory employs a probability weighting function where events with a higher exceedance-probability obtain a lower weight compared to expected utility, whereas low exceedance-probability events are overweighed(40). The general prospect theory value of a prospect is(40):

$$E(U(x)) = \int \frac{p_i^{\delta}}{(p_i^{\delta}+(1-p_i)^{\delta})^{\frac{1}{\delta}}}(-\lambda(-x)^{\theta})dp_i \tag{22}$$

In the above equation, λ is a loss-aversion parameter. The parameter θ reflects constant relative risk aversion, and δ is the curvature of the probability weighting function. Overall, using prospect theory alters both the insurance penetration rate in voluntary and semi-voluntary flood insurance markets and the incentivised risk reduction.

SI6.6.2 Alternate functional form of the utility function

We also examine how sensitive our results are to assuming an alternative specification of the utility function of subjective expected utility theory, which has been proposed by some studies(41):

$$E(U) = \begin{cases} E(U_{1,i,j,t,s}) = \int_0^{p=\widetilde{PS}_j} p \frac{(W_{i,j,t} - \gamma_{i,j} L_{j,t}(p))^{1-\theta}}{1-\theta} dp \\ E(U_{2,i,j,t,s}) = \int_0^{p=\widetilde{PS}_j} p \frac{(W_{i,j,t} - 0.15\gamma_{i,j} L_{j,t}(p)-)^{1-\theta}}{1-\theta} dp \end{cases} \tag{23}$$

In Eq. (23), θ is now assumed to be normally distributed with a mean equal to 1 and a standard deviation equal to 0.025. This distribution will produce many σ values close to 1 (and hence a logarithmic utility function), but some households will be more or less risk averse than others. Randomly drawn values equal to 1 are assumed to generate a logarithmic utility function.

Overall, the results of the sensitivity analyses with the utility function based on prospect theory and the alternative specification in Eq. 23 indicate that the ranking of insurance market structures remains very similar, with the PPP or the semi-voluntary (PPP) market structures being ranked the highest.

SI6.6.3 Flood risk perceptions

The sensitivity of the results to the flood occurrence perception distribution is tested by altering Eq. (13) in two ways. The first is by setting $\gamma_{i,j}$ equal to 1. In doing so, the average penetration rates double for the two voluntary markets, but now a greater number of households find the risk reduction measures unaffordable. This has the effect of adding three more countries where a PPP structure is optimal by 2035–2055, although the optimality of most markets remained the same, as illustrated in Figure 2. The second is by using the objective rather than subjective flood probabilities. The difference in estimated penetration rates is thus smaller on the whole, resulting in no noticeable differences in the final optimal market for each country.

SI6.7 Continuous MCA ranking

The primary MCA evaluation method was based on ordinal scores. However, in this section, we examine the sensitivity of the results to using a continuous score, as shown in Eq. (24).

$$MCA_{m,j,t,s} = \begin{cases} \frac{A_{m,j,t,s}}{A_{m,j,t,s}^{Max}} & if\ a\ benefit \\ 1 - \frac{A_{m,j,t,s}}{A_{m,j,t,s}^{Max}} & if\ a\ cost \end{cases} \tag{24}$$

Although this changes the value of the scores, the overall rankings of the market structures do not differ from the MCA with the ordinal ranking.

Moreover, for our baseline results, we used 11 sets of weights and compressed them into an overall score. If 24 and 35 unique sets of weights are used instead, then no noticeable influence is observed regarding the manner of ranking market structures. These weights are all based on expert judgement to produce a wide range of different public policy objectives.

SI7. DIFI model outcomes

SI7.1 Model output Table SI7.1. Examples of estimated criterion values for 2015-2035 that are used in the comparative analysis of market outcomes

	Voluntary Private	**Voluntary PPP**	**Semi-Voluntary Private**	**Semi-Voluntary PPP**	**PPP**	**Solidarity Public**
Net Present Value of Total Risk Reduction Incentivized (mill EUR)						
Austria	160	170	680	680	410	0
Belgium	160	160	470	470	310	0
Germany	440	440	900	860	870	0
Denmark	7	8	21	21	21	0
Spain	310	320	810	820	380	0
Finland	8	8	59	59	86	0
France	790	810	2,500	2,600	3,300	0
Ireland	17	17	51	51	55	0
Italy	610	630	1,500	1,500	840	0
Netherlands	5	5	14	14	18	0
Sweden	0	0	21	0	0	0
United Kingdom	35	36	120	120	140	0
Bulgaria	470	480	1,800	1,800	1,400	0
Czech Republic	8	8	47	48	0	0
Estonia	86	89	410	410	160	0
Greece	0	0	0	0	0	0
Croatia	27	28	97	98	50	0
Hungary	0	0	0	0	0	0

Lithuania	77	81	580	590	140	0
Luxembourg	0	0	2	2	0	0
Latvia	7	7	41	41	30	0
Poland	180	190	710	710	300	0
Portugal	11	12	25	25	11	0
Romania	110	120	460	470	9	0
Slovenia	19	20	87	88	38	0
Slovakia	51	53	310	310	150	0
Net Present Value of Total Unaffordability (mill EUR)						
Austria	890	810	880	810	190	36
Belgium	370	340	370	340	140	5
Germany	1,700	1,600	1,700	1,600	1,500	27
Denmark	160	140	160	140	10	0
Spain	2,800	2,600	2,800	2,600	240	11
Finland	9,000	8,700	9,000	8,700	180	22
France	13,000	12,000	13,000	12,000	3,200	110
Ireland	500	460	500	460	31	2
Italy	2,300	2,100	2,300	2,100	660	23
Netherlands	51	48	51	48	11	0
Sweden	160	150	150	150	150	12
United Kingdom	2,400	2,200	2,400	2,200	61	2
Bulgaria	4,300	3,900	4,300	3,900	790	14
Czech Republic	1,900	1,800	1,900	1,800	21	6

Estonia	1,200	1,100	1,200	1,100	110	6
Greece	910	850	910	850	6	0
Croatia	1,700	1,600	1,700	1,600	37	9
Hungary	3	2	3	2	0	0
Lithuania	3,300	3,000	3,200	3,000	130	16
Luxembourg	1,500	1,400	1,500	1,400	15	2
Latvia	1,000	960	1,000	960	21	2
Poland	5,700	5,300	5,600	5,300	220	130
Portugal	470	440	470	440	15	0
Romania	3,600	3,300	3,600	3,300	130	24
Slovenia	240	220	240	220	12	1
Slovakia	810	730	800	730	48	29
Net Present Value of Cost on Low-Risk Households (per household)						
Austria	0	0	0	0	91,000	120,000
Belgium	0	0	0	0	75,000	110,000
Germany	0	0	0	0	32,000	120,000
Denmark	0	0	0	0	240,000	260,000
Spain	0	0	0	0	270,000	300,000
Finland	0	0	0	0	260,000	270,000
France	0	0	0	0	200,000	250,000
Ireland	0	0	0	0	87,000	95,000
Italy	0	0	0	0	180,000	230,000
Netherlands	0	0	0	0	36,000	49,000

Sweden	0	0	0	0	1,500	10,000
United Kingdom	0	0	0	0	660,000	690,000
Bulgaria	0	0	0	0	520,000	630,000
Czech Republic	0	0	0	0	200,000	200,000
Estonia	0	0	0	0	80,000	89,000
Greece	0	0	0	0	170,000	180,000
Croatia	0	0	0	0	540,000	550,000
Hungary	0	0	0	0	74,000	74,000
Lithuania	0	0	0	0	94,000	99,000
Luxembourg	0	0	0	0	120,000	130,000
Latvia	0	0	0	0	54,000	56,000
Poland	0	0	0	0	270,000	270,000
Portugal	0	0	0	0	280,000	290,000
Romania	0	0	0	0	110,000	120,000
Slovenia	0	0	0	0	38,000	42,000
Slovakia	0	0	0	0	67,000	68,000
Average Penetration Rate (as a percentage)						
Austria	16	16	75	75	85	100
Belgium	23	23	75	75	85	100
Germany	32	33	75	75	85	100
Denmark	23	25	75	75	85	100
Spain	19	20	75	75	85	100
Finland	5	5	75	75	85	100

France	14	14	75	75	85	100
Ireland	16	17	75	75	85	100
Italy	23	24	75	75	85	100
Netherlands	18	18	75	75	85	100
Sweden	14	14	75	75	85	100
United Kingdom	13	14	75	75	85	100
Bulgaria	15	15	75	75	85	100
Czech Republic	2	2	75	75	85	100
Estonia	9	9	75	75	85	100
Greece	1	1	75	75	85	100
Croatia	9	10	75	75	85	100
Hungary	7	7	75	75	85	100
Lithuania	4	4	75	75	85	100
Luxembourg	2	3	75	75	85	100
Latvia	4	4	75	75	85	100
Poland	9	9	75	75	85	100
Portugal	12	13	75	75	85	100
Romania	8	8	75	75	85	100
Slovenia	8	9	75	75	85	100
Slovakia	6	7	75	75	85	100
			MCA Scores			
Austria	0.30	0.32	0.68	0.70	0.61	0.50

Belgium	0.34	0.37	0.67	0.69	0.61	0.50
Germany	0.38	0.40	0.66	0.67	0.65	0.50
Denmark	0.34	0.37	0.66	0.68	0.73	0.50
Spain	0.35	0.37	0.67	0.69	0.57	0.50
Finland	0.24	0.25	0.62	0.63	0.74	0.50
France	0.30	0.31	0.64	0.65	0.71	0.50
Ireland	0.32	0.35	0.67	0.68	0.73	0.50
Italy	0.35	0.38	0.67	0.69	0.57	0.50
Netherlands	0.31	0.33	0.68	0.69	0.72	0.50
Sweden	0.20	0.23	0.68	0.45	0.35	0.50
United Kingdom	0.30	0.33	0.66	0.68	0.73	0.50
Bulgaria	0.30	0.33	0.68	0.70	0.67	0.50
Czech Republic	0.27	0.28	0.70	0.71	0.46	0.50
Estonia	0.29	0.31	0.69	0.71	0.56	0.50
Greece	0.20	0.22	0.44	0.45	0.46	0.50
Croatia	0.31	0.33	0.69	0.70	0.59	0.50
Hungary	0.35	0.39	0.69	0.69	0.49	0.50
Lithuania	0.25	0.27	0.69	0.71	0.52	0.50
Luxembourg	0.26	0.28	0.70	0.70	0.46	0.50
Latvia	0.27	0.28	0.70	0.71	0.65	0.50
Poland	0.30	0.32	0.69	0.70	0.56	0.50
Portugal	0.37	0.39	0.68	0.70	0.57	0.50
Romania	0.30	0.32	0.69	0.71	0.47	0.50

Slovenia	0.29	0.31	0.69	0.71	0.58	0.50
Slovakia	0.27	0.29	0.69	0.71	0.58	0.50

Table SI7.2. Examples of estimated criterion values for 2035-2055 that are used in the comparative analysis of market outcomes

	Voluntary Private	**Voluntary PPP**	**Semi-Voluntary Private**	**Semi-Voluntary PPP**	**PPP**	**Solidarity Public**
Net Present Value of Total Risk Reduction Incentivized (mill EUR)						
Austria	187	194	778	780	672	0
Belgium	215	222	599	600	560	0
Germany	700	680	1,400	1,300	1,400	0
Denmark	5	5	13	13	17	0
Spain	338	350	900	900	630	0
Finland	0	0	0	0	0	0
France	650	660	2,640	2,647	3,790	0
Ireland	13	14	42	42	52	0
Italy	794	817	2,000	2,000	1,560	0
Netherlands	0	0	0	0	0	0
Sweden	9	8	72	38	51	0
United Kingdom	30	30	100	100	130	0
Bulgaria	507	525	1,971	1,976	1,941	0
Czech Republic	10	10	40	40	0	0
Estonia	98	101	490	490	379	0
Greece	0	0	0	0	0	0
Croatia	0	0	0	0	0	0

Hungary	0	0	0	0	0	0
Lithuania	78	82	668	674	505	0
Luxembourg	0	0	0	0	0	0
Latvia	2	2	18	18	39	0
Poland	175	182	739	743	688	0
Portugal	0	0	0	0	0	0
Romania	123	129	578	583	288	0
Slovenia	21	22	107	108	97	0
Slovakia	61	63	392	397	338	0
Net Present Value of Total Unaffordability (mill EUR)						
Austria						
Belgium	1,130	1,040	1,120	1,040	240	37
Germany	500	500	500	500	195	5
Denmark	2,100	1,900	2,100	1,900	1,800	26
Spain	200	200	200	200	11	0
Finland	3,800	3,500	3,800	3,500	330	11
France	20,000	19,600	20,000	19,600	404	22
Ireland	37,200	36,300	37,000	36,300	8,664	109
Italy	701	648	698	648	44	2
Netherlands	3,500	3,300	3,500	3,300	980	26
Sweden	100	100	100	100	18	0
United Kingdom	200	200	200	200	199	11
Bulgaria	3,400	3,100	3,400	3,100	90	0

Czech Republic	5,840	5,390	5,810	5,390	1,123	16
Estonia	3,300	3,200	3,300	3,200	40	5
Greece	1,980	1,850	1,960	1,850	183	6
Croatia	1,500	1,500	1,500	1,500	11	0
Hungary	0	0	0	0	0	0
Lithuania	4	4	4	4	0	0
Luxembourg	5,163	4,818	5,127	4,818	229	16
Latvia	2,481	2,349	2,474	2,349	25	1
Poland	1,810	1,700	1,802	1,700	38	2
Portugal	8,739	8,190	8,700	8,190	376	120
Romania	856	806	854	806	28	0
Slovenia	6,523	6,139	6,493	6,139	246	28
Slovakia	404	376	401	376	22	1
Net Present Value of Cost on Low-Risk Households (per household)						
Austria	0	0	0	0	204,900	258,000
Belgium	0	0	0	0	200,000	300,000
Germany	0	0	0	0	100,000	300,000
Denmark	0	0	0	0	510,000	550,000
Spain	0	0	0	0	660,000	730,000
Finland	0	0	0	0	520,000	540,000
France	0	0	0	0	500,000	600,000
Ireland	0	0	0	0	140,000	150,000
Italy	0	0	0	0	460,000	570,000

Netherlands	0	0	0	0	50,000	60,000
Sweden	0	0	0	0	3,000	22,000
United Kingdom	0	0	0	0	1,480,000	1,540,000
Bulgaria	0	0	0	0	1,350,000	1,610,000
Czech Republic	0	0	0	0	480,000	490,000
Estonia	0	0	0	0	191,000	212,000
Greece	0	0	0	0	260,000	260,000
Croatia	0	0	0	0	0	0
Hungary	0	0	0	0	130,000	130,000
Lithuania	0	0	0	0	230,000	240,000
Luxembourg	0	0	0	0	180,000	190,000
Latvia	0	0	0	0	80,000	90,000
Poland	0	0	0	0	690,000	700,000
Portugal	0	0	0	0	710,000	730,000
Romania	0	0	0	0	280,000	290,000
Slovenia	0	0	0	0	60,000	70,000
Slovakia	0	0	0	0	130,000	140,000
			Average Penetration Rate (as a proportion)			
Austria	16	16	75	75	85	100
Belgium	23	23	75	75	85	100
Germany	32	33	75	75	85	100
Denmark	23	25	75	75	85	100
Spain	19	20	75	75	85	100

Finland	5	5	75	75	85	100
France	14	14	75	75	85	100
Ireland	16	17	75	75	85	100
Italy	23	24	75	75	85	100
Netherlands	18	18	75	75	85	100
Sweden	14	14	75	75	85	100
United Kingdom	13	14	75	75	85	100
Bulgaria	15	15	75	75	85	100
Czech Republic	2	2	75	75	85	100
Estonia	9	9	75	75	85	100
Greece	1	1	75	75	85	100
Croatia	9	10	75	75	85	100
Hungary	7	7	75	75	85	100
Lithuania	4	4	75	75	85	100
Luxembourg	2	3	75	75	85	100
Latvia	4	4	75	75	85	100
Poland	9	9	75	75	85	100
Portugal	12	13	75	75	85	100
Romania	8	8	75	75	85	100
Slovenia	8	9	75	75	85	100
Slovakia	6	7	75	75	85	100
			MCA Scores			

Austria	0.30	0.32	0.68	0.70	0.70	0.50
Belgium	0.34	0.37	0.67	0.69	0.66	0.50
Germany	0.38	0.40	0.66	0.66	0.66	0.50
Denmark	0.31	0.34	0.62	0.64	0.72	0.50
Spain	0.35	0.37	0.67	0.69	0.64	0.50
Finland	0.25	0.26	0.66	0.66	0.74	0.50
France	0.27	0.28	0.62	0.63	0.71	0.50
Ireland	0.31	0.33	0.65	0.66	0.73	0.50
Italy	0.35	0.38	0.67	0.69	0.64	0.50
Netherlands	0.30	0.32	0.67	0.68	0.72	0.50
Sweden	0.26	0.27	0.68	0.58	0.52	0.50
United Kingdom	0.28	0.30	0.63	0.65	0.73	0.50
Bulgaria	0.31	0.33	0.68	0.70	0.71	0.50
Czech Republic	0.26	0.27	0.70	0.71	0.49	0.50
Estonia	0.28	0.30	0.69	0.70	0.67	0.50
Greece	0.20	0.22	0.44	0.45	0.46	0.50
Croatia	0.29	0.31	0.67	0.69	0.73	0.50
Hungary	0.34	0.37	0.67	0.71	0.72	0.50
Lithuania	0.25	0.26	0.69	0.71	0.67	0.50
Luxembourg	0.20	0.22	0.44	0.45	0.46	0.50
Latvia	0.23	0.24	0.55	0.56	0.74	0.50
Poland	0.30	0.31	0.69	0.70	0.72	0.50
Portugal	0.30	0.32	0.59	0.60	0.73	0.50

Romania	0.29	0.30	0.69	0.70	0.58	0.50
Slovenia	0.28	0.30	0.69	0.70	0.72	0.50
Slovakia	0.26	0.28	0.69	0.71	0.70	0.50

Table SI7.3. The highest scoring multi-criteria analysis results compared to the current insurance market structure.

Country	Current insurance market structure	Highest scoring insurance market structure over 2015-2035	Highest scoring insurance market structure over 2035-2055
Austria	Voluntary Private	Semi-voluntary (PPP)	PPP
Belgium	Solidarity Public	Semi-voluntary (PPP)	Semi-voluntary (PPP)
Germany	Voluntary Private	PPP	PPP
Denmark	Voluntary Private	PPP	PPP
Spain	Solidarity Public	Semi-voluntary (PPP)	Semi-voluntary (PPP)
Finland	Voluntary Private	PPP	PPP
France	Solidarity Public	PPP	PPP
Ireland	Semi-voluntary Private	PPP	PPP
Italy	Voluntary market	Semi-voluntary (PPP)	Semi-voluntary (PPP)
Netherlands	Solidarity Public	Semi-voluntary (PPP)	Semi-voluntary (PPP)
Sweden	Semi-voluntary Private	PPP	PPP
United Kingdom	PPP	Semi-voluntary (PPP)	PPP
Bulgaria	Voluntary Private	Semi-voluntary (PPP)	Semi-voluntary (PPP)
Czech Republic	Voluntary Private	Semi-voluntary (PPP)	Semi-voluntary (PPP)
Estonia	Voluntary Private	Solidarity Public	Solidarity Public
Greece	Voluntary Private	Semi-voluntary (PPP)	PPP
Croatia	Voluntary Private	Semi-voluntary (PPP)	Semi-voluntary (PPP)
Hungary	Semi-voluntary Private	Semi-voluntary (PPP)	Semi-voluntary (PPP)
Lithuania	Voluntary Private	Semi-voluntary (PPP)	Solidarity Public
Luxembourg	Voluntary Private	PPP	PPP
Latvia	Voluntary Private	Semi-voluntary (PPP)	PPP
Poland	Voluntary Private	Semi-voluntary (PPP)	PPP
Portugal	Voluntary Private	Semi-voluntary (PPP)	PPP
Romania	Solidarity Public	Semi-voluntary (PPP)	Semi-voluntary (PPP)
Slovenia	Voluntary Private	Semi-voluntary (PPP)	PPP
Slovakia	Voluntary Private	Semi-voluntary (PPP)	Semi-voluntary (PPP)

SI7.2 Results for specific evaluation criteria

The average household insurance premiums are lowest in the solidarity public structure (€5–€125 per year in 2015) and highest in private voluntary markets (€30–€2000 per year in 2015) (SI7). Premiums fall for higher degrees of cross-subsidisation of premiums between high- and low-risk households. The magnitude of unaffordability follows a similar pattern because premiums are more likely to be unaffordable for low-income households in private voluntary markets where they are based on objective flood risk with little cross-subsidisation. On average, across NUTS 2 regions, the voluntary private insurance premiums are unaffordable for about 21% of the regional population in high-risk areas, whereas this is only the case for 16% in the PPP market. With cross-subsidisation, the percentage of the population facing unaffordable insurance only falls by 5% (to 11%), the NPV associated with unaffordable premiums falls by 60% on average. This result implies that the PPP structure considerably decreases premium costs for low-income households.

However, the cost for low-risk households is lowest when premiums are based on risk. In that case, high-risk households must pay more of their expected loss themselves. For instance, under the voluntary market structures, the NPV of the direct subsidy between high- and low-risk households is €0; by contrast, under the solidarity structure in the Netherlands, the UK and Sweden, the NPV of this subsidy between 2015 and 2035 is predicted by the model to be roughly €300 million in total. This indicates that increasing the degree of risk sharing may impose high costs on low-risk households for which they receive no direct benefits.

The modelled insurance penetration rates are stable over time, and the modelled voluntary private market penetration rates are about 75% lower than those for the markets with purchase requirements. However, this case may be the result of assuming that incomes grow equally at the rate of exposure.

The insurance-based risk reduction incentives are not found to be effective in the solidarity public structure because the premium discount that policyholders receive for implementing risk reduction measures is too low (an average of €14 per year in 2055).

The PPP markets are found to be more successful in incentivising dry flood-proofing (measures aimed at preventing water from entering a building) because the annual financial incentive to implement those measures is nearly four times as large as in the solidarity public structures. These incentives in the PPP market are less effective in stimulating wet flood-proofing measures aimed at limiting damage once water has entered a building due to their higher investment costs.

The modelled voluntary market structures offer stronger incentives in terms of premium discounts of, on average, €500 per year, which make flood-proofing measures cost effective for many households. However, fewer households are exposed to this incentive due to the lower market penetration rate of flood insurance. Moreover, the high premium discounts for risk mitigation imply that insured households are more likely to find the measures cost effective; however, the size of the premium may result in the household being unable to afford risk reduction measures.

SI7.3 Drivers of flood risk

While not the main focus of the DIFI model, we can also provide an initial disentangling of the drivers of flood risk across the different flood insurance market structures in a holistic sense. Climate change increases flood risk in some EU regions, whereas it decreases risk in others. On average, these effects cancel each other out across the NUTS 2 regions studied. However, climate change impacts on flood risk significantly vary across NUTS 2 regions as the maximum change associated with climate change was an increase in flood risk of 40%, whereas the smallest was a fall of 29%. The socioeconomic contribution to risk which increases exposure to flooding was a more consistently strong driver, by causing a doubling of risk per household, on average, with a minimum and a maximum increase of 27% and 166%, respectively. Moreover, population changes alter the concentration of risk and average premiums. Areas with an expected falling population (e.g. the Baltic countries) will face sharper increases in average insurance premiums because there are fewer households to share risk over; on the contrary, areas with an expected increasing population (e.g. the UK) may face a shallower increase due to improved risk sharing.

However, the above disregarded the automatic adaptation behaviour of households towards changing risk. Although on average households tend to underestimate risk (see SI4.2), those households that are highly exposed to flooding do undertake some level of risk reduction(5, 16, 17). The optimal insurance market structure increases household flood preparedness. This aspect is highlighted in Figure 3A (in the main manuscript), indicating that, for the most part, moving towards the optimal market structure increases the reduction in flood risk due to insurance incentives compared to a region's current flood insurance market practice.

SI7.4 Welfare consequences for households of flood insurance reforms

Suitable flood insurance reforms can increase the welfare of the high-risk households by lowering premiums and increasing coverage.

Insurance coverage can improve the welfare of a risk-averse household by exchanging a large, uncertain and potentially catastrophic loss from a flood for a certain, fixed smaller payment in the form of the insurance premium. Therefore, a higher market penetration of flood insurance can be viewed as welfare-enhancing because of improved financial coverage against flood damage. We find that the coverage gap (i.e. households without flood insurance) is expected to grow without flood insurance reform, whereas it can be limited by moving towards the optimal insurance markets. For ~81% of the countries studied, introducing stronger requirements to purchase flood insurance or a cap on premiums yields higher penetration rates. For example, the penetration rate in areas with a high flood risk in Eastern Europe is on average ~8% over 2015 to 2055, which increases ~78% under the proposed flood insurance reforms (assuming the presence of effective enforcement).

Another welfare benefit of the proposed flood insurance market reforms arises from lower premiums, which implies that the risk transfer is achieved at a lower cost. In particular, introducing the PPP market structure substantially reduces premiums for high-risk households in many countries; premiums even fall by over 80% in 11 countries. However, this does come at the expense of low-risk households that are now compelled to buy insurance at a small price. This cross-subsidy slightly lowers the welfare of these households, although the total net welfare benefit is positive, as the lower premium for high-risk households in the PPP outweighs the small premium increases for low-risk households. A more modest premium reduction occurs for countries that introduce the semi-voluntary (PPP) market structure. The welfare increase for these markets is likely to be less ambiguous than under the PPP structure because the penetration rate increases, premiums are lower and a formal premium cross-subsidy is lacking.

Welfare effects are different for the four countries; for these countries, moving away from their current purely solidarity-based systems to either the PPP or semi-voluntary (PPP) flood insurance markets is optimal. In these cases, the penetration rate drops by between 15% and 25%[26], which implies a larger coverage gap, and premiums increase for high-risk households. First, premiums decline for low-risk households that are no longer required to purchase flood insurance in the new market structures. Second, the higher premiums for high-risk households create stronger risk reduction incentives, which stimulate the flood-proofing of properties. The resulting risk reduction brings welfare benefits in terms of lower expected deductibles and premiums. Although the coverage gap has increased in these four markets, the total level of risk and costs for low-risk households are lower than without reforms, resulting in a potential welfare gain.

SI8. Method used to develop the evaluation criteria and allocate countries to the stylised market structures

SI8.1 Evaluation criteria

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[26] Romania represents an exception, whereby a stronger compulsion compared to the current situation may actually increase the penetration rate. This is because currently the purchase requirement is not strongly enforced.

SI8.1.1 Evaluation criteria: literature-based development

The evaluation criteria are based on the debate surrounding flood insurance mechanisms in the household (or private property) insurance market for extreme weather events, with a focus on flooding, as collected through a literature review. We derived the criteria from the perspective of a policymaker because disaster insurance is a public policy choice that aims to fulfil certain risk management objectives(42, 43). To investigate these objectives, the documents listed below were consulted, and we reviewed the consultation documents surrounding the European Commission's Green Paper on the Insurance of Natural and Man-made Disasters (that were published in English).

We reviewed the publicly available documents that focused on the policy debate surrounding extreme weather insurance(for example, 1-3, 6, 25, 26, 42-63). From these documents, we isolated the following overall important outcomes or characteristics of extreme weather insurance, of which flooding is the most pressing issue(64): (1) the overall insurance penetration rate, (2) incentivised risk mitigation, (3) ability to absorb large losses, (4) capacity to provide quick and certain compensation, and (5) the affordability and availability of insurance.

In the subsequent step, the desirable criteria had to be further operationalised to allow for their modelling within the DIFI framework. The criteria are presented in Table SI8.A. Criteria 1 and 2 are the same as the aforementioned desirable characteristics. These criteria can be readily modelled using the approaches developed by Savage(12) and Hudson et al.(11) regarding subjective utility approaches. The Solvency II EU legislation requires the compliance of European insurers to an annual insolvency probability of 0.5% (i.e. a 1/200-yr flood event). Therefore, insurers are already regulated to be able to absorb large losses, which implies that characteristic 3 is met and excluded as a separate criterion in our study. Similarly, characteristic 4 is met by the formal flood insurance arrangements studied here, which are assumed to provide quick and certain compensation due to competitive or legal pressures. Characteristic 5 is further refined into costs imposed on low-risk households (criterion 3 in Table SI8.A) and unaffordability of insurance for high-risk households (criterion 4 in Table SI8.A) to capture the core equity concerns. Criterion 3 depicts the concern that people who are not at risk of flooding are forced to bear an additional burden, for which they gain no direct benefit due to the choices of those living in flood-prone areas. Criterion 4 encapsulates equity concerns about the burden that the premiums place on flood-prone households and determines if this burden is excessive for these households(11, 32, 65, 66).

Hochrainer-Stigler and Lorant (67) present an MCA of disaster risk management partners, which can be compared to insurance markets. Their selected criteria are economic efficiency (costs of insurance), risk reduction incentives, equity (solidarity and decreasing inequalities) and feasibility. They developed the criteria through an independent process involving a different range of stakeholders. Nevertheless, our four evaluation criteria closely match the criteria of Hochrainer-Stigler and Lorant, indicating the overall suitability of the operationalised evaluation criteria.

Table SI8.A. Summary and definition of the evaluation criteria estimated by the DIFI model

	Definition	**Benefit/Cost**
Criterion 1: Insurance penetration rate	The average percentage of households with high flood risk that buy insurance at the national level	Benefit
Criterion 2: Incentivised risk reduction	The total net present value (NPV) of incentivised risk reduction conducted by households at the national level	Benefit
Criterion 3: Cost on low-risk households	The NPV of the subsidy of high-risk households paid by low-risk households; aggregated to the national level	Cost
Criterion 4: Unaffordability of insurance	The NPV of the magnitude of unaffordability, measured as the portion of premiums that cannot be paid from a poverty-adjusted disposable income at the national level	Cost

SI8.1.2 Evaluation criteria: supplementary check by stakeholder consultation

As a supplementary analysis of the validity of desirable criteria (and the resulting evaluation criteria), expert stakeholders from across Europe were consulted to judge if these defined objectives matched their objectives in practice. This information was obtained from a series of stakeholder workshops held in Brussels, a webinar and a series of expert interviews conducted by telephone and email. Attempts were made to contact stakeholders from all countries across the European Union. However, gaps emerged in the responses across member states and/or type of stakeholders. Nevertheless, a spread between Southern, Northern, Eastern and Western European countries was achieved, and EU-wide stakeholders were represented (Table SI8.B). Therefore, this stage of the research process can be considered as an additional qualitative check of the results presented in SI8.1.1.

The first method of contact with expert stakeholders was through surveys that could be completed via return email, telephone calls or a combination of both. The survey asked respondents the following groups of questions: what the most important risk management objective is for extreme weather insurance; a self-stated weighting (in terms of importance or relevance) of the five proposed desirable outcomes/characteristics for natural disaster insurance, of which the weights provided by the respondents should be equal to the sum of 1, along with a justification of their choices; and a self-stated assessment and description of the insurance market with which the respondent is most familiar. Table SI8.B presents the 25 stakeholders who responded.

Table SI8.B. Stakeholder responses to the questionnaire

Country	
Bulgaria	1 private sector insurer (DZI)
Romania	1 insurer (PAID) 1 academic (INHGA)
Hungary	Hungarian insurance association
Sweden	Insurance Sweden 4 private insurers (Länsförsäkringar AB, If P&C insurance Ltd, AIG Europe Limited, Trygg Hansa)
Denmark	Danish Insurance Association Danish Storm Council
France	2 academics (University of Montpellier 3 Paul Valéry, Ecole Polytechnique) 1 public insurer (CCR) 1 public body (MRN)
UK	1 charity (National Flood Forum)
Germany	German Insurance Association
Austria	Austrian Insurance Association
Italy	Italian Insurance Association
Spain	1 public insurer (CCS) 1 academic (FEEM)
EU-wide	OECD Researcher (wanted anonymity) Insurance Europe FERMA

Table SI8.C presents the average weighting of the five proposed desirable criteria reported from the stakeholders. On average across stakeholders, each element of the evaluation criteria is indeed important. The desirable criteria were all roughly equally important, although a slight focus on insurance penetration rates and risk signalling was evident. However, the responses also highlighted differences in stakeholder preferences; for instance, the charity stakeholder from the UK indicated that risk signalling was unimportant and that insurance should achieve high degrees of affordability and coverage instead.

Table SI8.C. Stakeholder responses to the questionnaire

Criteria	Average Weighting
Insurance penetration rate	0.23
Risk signaling	0.22

Ability to absorb large losses	0.19
Affordability and availability	0.19
Quick and certain compensation	0.18

The results of the stakeholder interviews were supported by a stakeholder workshop held in Brussels in April 2017 and a webinar in June 2017 (see Table SI8.D for the participants). Both events discussed insurance coverage gap, lack of incentives for risk reduction, stakeholder collaboration and PPPs. These discussions tended to be focused more on the problems of insuring fluvial flood risk compared to other extreme weather events. An important outcome from these discussions for the DIFI model framework was that modelling the overall evaluation of insurance markets through our MCA-based approach was deemed to be acceptable. The MCA approach was generally viewed as appropriate because insurance markets are expected to simultaneously meet multiple objectives, which requires trade-offs between the criteria. An MCA-based approach was judged as being capable of achieving this target, in addition to allowing for different subjective weights of the criteria.

Table SI8.D. Stakeholders who contributed to the focus group workshop and webinar

Country	
Austria	GRAWE / VVO
Denmark	City of Copenhagen
Denmark	Forsikring og Pension
EU-wide	Insurance Europe
EU-wide	ICLEI - Local Government for Sustainability
EU-wide	OECD
France	Mission Risques Naturels
Germany	Allianz
Germany	Munich Re
Germany	MCII
Norway	Finance Norway
Switzerland	Swiss Re
Switzerland	Zurich Insurance
UK	London School of Economics
UK	ClimateWise

The purpose of the stakeholder engagement process was to obtain a qualitative check of the MCA criteria and weighting that were derived from the literature review. We acknowledge that our sample of stakeholders is not fully representative across Europe and sectors; thus, we did not base the final criteria on the stakeholder consultation but instead derived these criteria from the wider literature. The results provided in Table SI8.C denote that the stakeholders indicated that all of the five desirable criteria have a degree of importance, and hence are potentially suitable for the final evaluation criteria. This result provides confidence in the criteria that were selected on the basis of the literature review. Hence, we decided to use these criteria and weights that systematically express different risk management objectives. This MCA approach is similar to what has been used in Unterberger et al. (2019) who conduct an MCA for public sector flood insurance arrangements.

SI8.2 Stylised market structures

The stylised market structures are based on the following key elements:

1) If the purchase is mandated by law, if the purchase is required by dwelling-related conditions (i.e. mortgage or rental conditions) or if the purchase is completely voluntary. The first two cases are also examples of where flood insurance coverage tends to be sold in a bundle with other risks (e.g. windstorm, household fire).
2) The degree to which premiums are believed to be risk-based: risk-based, a known cap on premiums, or if premiums are unconnected to the risk faced by a policyholder and instead are offered at fixed rates.

3) Governmental support in the case of large-scale flood events. This element is further subdivided into two considerations:
    a. Provision of governmental compensation to households after a flood event: no compensation, uncertain compensation, certain compensation
    b. Provision of governmental support for the insurance industry: no governmental support, governmental support is present

A country is allocated to a stylised market based on how closely a market meets these aspects of the markets M1–M6. The first two considerations are purchase requirements and the connection between premiums and risk. These points of comparison are the most fundamental aspects of the market that generate the aforementioned evaluation criteria. The reason is that requirements drive insurance penetration rates(50, 68), which can be influenced by legal obligations or by product design(69) and the demand for these products. The link between premiums and risk can create significant trade-offs between affordability and the ability to incentivise risk reduction(11). Finally, the combination of these two features determines the required cross-subsidy between high- and low-risk policyholders.

Once the initial decision for a market allocation has been made based on the first two conditions, then the decision is refined by the role of the government in the market in terms of the degree of governmental support available for the insurance industry and households affected by flooding. For instance, offering both public compensation after a disaster event while also providing formal support for the insurance industry constitute a rare practice for a country(43). The role of public reinsurance is to help to keep premiums low by replacing potentially high private (risk-averse) reinsurance premiums with a lower public (risk-neutral) reinsurance premium. Finally, the presence of governmental compensation can create charity hazard, which reduces the demand of insurance, as the consequence of not being insured is lower(70). Both of these features are important for determining voluntary demand. Higher premiums can decrease the demand for insurance, and they are more likely to be found unaffordable, for example.

As an illustration, France was found to have a legal mandate to purchase disaster insurance with standard homeowners at fixed rates(71), which would place the market in M1. On the contrary, the UK has an informal mandate to buy insurance due to lender requirements(26), which would place the UK in M2 or M6, but premiums are capped due to Flood Re(72). Moreover, Flood Re has a quasi-governmental framework to support the provision of indemnity payments in the case of extreme events(42). Together these features place the UK in M6. A third example is Austria, which has an optional voluntary insurance(73) to top up very limited cover in standard polices(74), and it follows the principle of risk-based premiums. Additionally, governmental compensation is given for flood losses through the Austrian Catastrophe Fund(73). Therefore, Austria was placed in the M3 stylised market structure. A final example is Slovakia. Slovakia was found to have an overall penetration rate of 50%(61, 75) (a higher rate than mortgage-backed buildings), an overall voluntary purchase of flood insurance with a capacity to opt-out, premiums that vary across regions and the capability of the Slovak state to provide ad-hoc compensation(61). Based on this information, Slovakia was allocated to M3 because this market structure allows for ad-hoc public compensation, and the consumer has the ability to opt-out of comprehensive coverage, which for example would be inconsistent with the (indirect) compulsion for buying flood insurance in the M2 markets.

Once the markets were allocated to M1–M6, information on insurance penetration rates was collected. Once information was gathered for each market structure, the most suitable range of penetration rates for that market classification was determined. For example, considering M1, Atreya et al.(61) revealed that Belgium, France and Spain have insurance penetration rates close to 100%. The European Commission reported a similar finding(43).

A similar approach was adopted for the countries in the semi-voluntary market structure (including the UK pre-flood Re)(for example, 26, 42, 76-78). These references revealed that between 75% and 100% of households are covered by flood insurance. Hungary proved to be a slight exception, with a penetration rate of 70–75%(43, 75). Moreover, household contents tend to be insured less than the buildings themselves(26), and lower income individuals are less likely to be insured(79). In contrast to the solidarity market, voluntary demand still plays a role in determining insurance coverage because full coverage (both building and contents coverage) is not required in the semi-voluntary market structure. A wider range of potential insurance penetration rates is applied to countries with this market structure to account for the observed variations in practice.

The voluntary market (M3) has a much broader scope of penetration rates ranging from less than 10% in Bulgaria, Greece or Italy(43, 75, 80) to 30–40% in Germany due to the presence of voluntary opt-outs(15, 78); meanwhile, flood coverage is virtually non-existent in the Netherlands(78). Therefore, for M3, the establishment of a consistent pattern for penetration rates for the countries as a whole is difficult. However, a noticeable pattern is that the presence of expected governmental compensation inhibits the development of insurance coverage. For example, the Austrian Catastrophe Fund provides (incomplete) compensation after flood events, and it can range between 20% and 50% of the damage(55, 73), contributing to the low penetration rate of (at most) 25%(73). By contrast, in Germany, compensation is less certain(81), which partly contributes to a higher penetration rate than Austria. Countries without a tradition of providing governmental compensation generally tend to have higher penetration rates(61), as the potential consequences of not being insured are higher. An additional observable pattern is that penetration rates do not reach the level of M2 when the purchase of insurance is a voluntary decision. These observations lead to the methodological choice to model the voluntary demand according to the consumer behaviour model described in SI4.

The rationale for aggregating information to the stylised market structures is that more detailed information about flood insurance arrangements is not always available, measured in a consistent manner, or freely and easily accessible across all countries in Europe(82). Therefore, these stylised market structures are less accurate for certain countries than others, while capturing the required level of detail for conducting the MCA to identify the relative benefits of the market structures. Additionally, introducing more detailed distinctions to our market structure would increase model complexity, and this step is only relevant to undertake if these features have a considerable influence on our modeled criteria.

In addition to the aforementioned references, further information was collected from the underlying literature and stakeholder consultations used for constructing the evaluation criteria. This further information was then combined to achieve an understanding of the main features of a flood insurance structure in a country, which are of influence on our evaluation criteria. However, not all information collected could be directly employed in the DIFI model framework. For example, flood insurance is often bundled with other natural hazard risks in countries with high penetration rates. In practice, such bundling often implies having indirectly mandated purchase requirements, as flood coverage is commonly bundled with other risks such as fire, for which having coverage to meet mortgage requirements is often compulsory. Therefore, in our solidarity, semi-voluntary and PPP markets, the insurance product could be considered as being part of a wider bundle of natural hazard risks without the opportunity to opt-out. By contrast, the product offered in the voluntary markets can be viewed as a separate insurance policy, or as an opt-in element of a broader insurance policy.

Set of additional selected references for SI8.1 and SI8.2:

These references are illustrative of those used in addition to those directly cited in SI8.1 and SI8.2:

Austrian Insurance Association 2016 (private communications)

Badea, D.G., 2008. The Romanian Catastrophe Insurance Scheme – PRAC. The Word Forum of Catastrophe Programmes, last access on 9/01/2017 at: http://www.wfcatprogrammes.com/c/document_library/get_file?folderId=19777&name=DLFE-1521.pdf

CCS (Consorcio de compensacion de seguros), 2016. Consorcio de compensacion de seguros: an overview, accessed on:

Danish Storm Council (Storm Raadet), 2015. Website last accessed 9/01/2017 at: http://www.stormraadet.dk/Menu/ordbog

DIZ, private inurance company (private communications)EC (European Commission), 2014. Final report of the Commission Expert Group on European Insurance Contact Law. The European Commission, last accessed on 9/01/2017 at: http://ec.europa.eu/justice/contract/files/expert_groups/insurance/final_report_en.pdf

German Insurance Association 2016 (private communications)

Insurance Europe 2016 (private communications)

Insurance Sweden 2016 (private communications)

Keskitalo, E.C.H., Vulturius, G., Scholten, P., 2014. Adaptation to climate change in the insurance sector: examples from the UK, Germany and the Netherlands, Natural Hazards, 71 315-334, doi: 10.1007/s11069-013-0912-7

Lamond, J., Penning-Rowsell, E., 2014. The robustness of flood insurance regimes given changing risk resulting from climate change, Climate Risk Management (2), 1-10.

Lamond, J., Proverbs, D., Hammond, F.N., 2009a. Accessibility of flood risk insurance in the UK: confusion, competition and complacency, Journal of Risk Research, 12 (6), 825-841

Maccaferri, S., Cariboni, F., Compolongo, F., 2012. Natural Catastrophes: Risk relevance and insurance coverage in the EU, http://ec.europa.eu/finance/insurance/docs/natural-catastrophes/jrc_report_on_nat_cat_en.pdf,

OECD (2015), Disaster Risk Financing: A global survey of practices and challenges, OECD Publishing, Paris. http://dx.doi.org/10.1787/9789264234246-en

PAD 2016 (private communications)

Penning-Rowsell, E.C., Pardoe, J., 2012. Who benefits and who loses from flood risk reduction? Environment and Planning C: Government and Policy, 30, 448-466

Pollner, J., 2012. Financial and Fiscal Instruments for Catastrophe Risk Management: Addressing Losses from Flood Hazards in Central Europe. The World Bank, Washington, D.C.

Porrini, D., Schwarze, R., 2012. Insurance models and European climate change policies: an assessment, European Journal of Law and Economics, 38 (1), 7-28

PUI (Polish Insurance Association), 2017. Website, last accessed on 09/01/2017 at: https://www.piu.org.pl/insurance-supported-by-the-state

Radu-Neacsu, N., 2014. Romanian Case Study of Compulsory Insurance: The PAID Insurance Framework. Europa Re Second Regional Insurance Conference: “New Generation of Insurance Solutions”, Belgrade, Serbia, 1-2 October 2014.

Surminski, S., Eldridge, J., 2015. Flood insurance in England – an assessment of the current and newly proposed insurance scheme in the context of rising flood risk, Journal of Flood Risk Management, DOI: 10.1111/jfr3.12127

Surminski, S., 2017. Fit for the future? The reform of flood insurance in Ireland: Resolving the data controversy and supporting climate change adaptation, Policy Paper, London School of Economics, London

Surminski S., Thieken, A., 2017. Promoting flood risk reduction: The role of insurance in Germany and England. Earth's Future, 5:979-1001.

Svensk Forsakring, 2016. Insurance in Sweden 2015. Website last accessed 9/01/2017 at: http://www.svenskforsakring.se/Global/Broschyrer/SF_Statistikbroschyr_2015_eng_final.pdf

Svenskforsakring (Insurance Sweden), 2013. Weather related damage in the Nordic countries – from an insurance perspective, last accessed on 11/01/2017 at: http://www.svenskforsakring.se/Global/Rapporter/Weather%20related%20damage%20in%20the%20Nordic%20countries%20(final).pdf?epslanguage=sv

Swiss Re, (2015). Underinsurance of property risks: closing the gap. Sigma,, No. 5/2015. Last accessed on 09/01/2017 at: http://www.riskandinsurance.com/wp-content/uploads/2015/10/Swiss-Re_Underinsurance-of-property-risks.pdf

UN (United Nations), 2007. National Information , last accessed on 9/01/2017 at: http://www.un.org/esa/agenda21/natlinfo/countr/sweden/

UN (United Nations), 2008. National Information, last accessed on 9/01/2017 at: http://www.un.org/esa/agenda21/natlinfo/countr/france/

Wharton Risk Management and Decision Processes Center (2016), Flood insurance around the world: Understanding residential flood insurance markets (beta version), https://riskcenter.wharton.upenn.edu/flood-insurance-around-the-world/, accessed 09/01/2017

World Bank, 2012. Chapter 8 –The French Experience on Disaster Risk Management, Improving the assessment of Disaster Risks to strengthen financial resilience, Washington D.C.

Insurance Europe 2018. NatCat Chart – Private Lines Austria. Accessed last: 28.11.2018, accessed at: https://bit.ly/2ztW7vQ

Insurance Europe 2018. NatCat Chart – Private Lines Belgium. Accessed last: 28.11.2018, accessed at: https://bit.ly/2ScZluy

Insurance Europe 2018. NatCat Chart – Private Lines Finland. Accessed last: 28.11.2018, accessed at: https://www.insuranceeurope.eu/sites/default/files/assets/NatCartChart-Finland-privatelines.pdf

Insurance Europe 2018. NatCat Chart – Private Lines France. Accessed last: 28.11.2018, accessed at: https://www.insuranceeurope.eu/sites/default/files/assets/NatCartChart-France-privatelines.pdf

Insurance Europe 2018. NatCat Chart – Private Lines Germany. Accessed last: 28.11.2018, accessed at: https://www.insuranceeurope.eu/sites/default/files/assets/NatCartChart-Germany-privatelines.pdf

Insurance Europe 2018. NatCat Chart – Private Lines Italy. Accessed last: 28.11.2018, accessed at: https://www.insuranceeurope.eu/sites/default/files/assets/NatCartChart-Germany-privatelines.pdf

Insurance Europe 2018. NatCat Chart – Private Lines Netherlands. Accessed last: 28.11.2018, accessed at: https://www.insuranceeurope.eu/sites/default/files/assets/NatCartChart-Netherlands-privatelines.pdf

Insurance Europe 2018. NatCat Chart – Private Lines Spain. Accessed last: 28.11.2018, accessed at: https://www.insuranceeurope.eu/sites/default/files/assets/NatCartChart-Spain-privatelines.pdf

Insurance Europe 2018. NatCat Chart – Private Lines Slovenia. Accessed last: 28.11.2018, accessed at: https://www.insuranceeurope.eu/sites/default/files/assets/NatCartChart- Slovenia-privatelines.pdf

Insurance Europe 2018. NatCat Chart – Private Lines Sweden. Accessed last: 28.11.2018, accessed at: https://www.insuranceeurope.eu/sites/default/files/assets/NatCartChart- Sweden-privatelines.pdf

SI Tables

Table SI1. Estimated cost functions and cost surcharges

	Insurer Cost Behaviour		
	Baseline cost function		
	Constant	Time Trend	
Fixed effects	-1.5	-0.071	
	(0.093)	(0.032)	
Random effect standard deviation	0.09	0.25	
	(0.027)	(0.084)	
N		122	
	Estimated surcharge as a percentage of the premium		
	2015	2035	2055
Austria	0.03	0	0
Belgium	0.15	0.03	0.01
Germany	0.05	0	0
Denmark	0.16	0.06	0.02
France	0.23	0.14	0.09
Spain	0.17	0.01	0
Finland	0.18	0.14	0.09
Ireland	0.1	0.01	0
Italy	0.26	0.2	0.15
The Netherlands	0.23	0.0	0.02
Sweden	0.15	0.05	0.02
The United Kingdom	0.11	0.02	0
Bulgaria	0.28	0.28	0.36
Czech Republic	0.14	0.02	0
Estonia	0.28	0.28	0.362
Greece	0.25	0.03	0
Croatia	0.28	0.28	0.36
Hungary	0.35	0.49	0.7
Lithuania	*0.28*	*0.276*	*0.362*
Luxembourg	*0.16*	*0.07*	*0.04*
Latvia	0.28	0.28	0.36
Poland	0.31	0.3	0.29
Portugal	0.25	0.19	0.14

Romania	0.28	0.28	0.36
Slovenia	0.28	0.28	0.36
Slovakia	0.35	0.54	0.82

Table SI2. A summary of the benefits and costs of household flood risk mitigation measures

Name of risk reduction measure	**Description**	**Effectiveness ratio (upper/lower bound)**	**Investment cost (upper/lower bound)**
Wet flood-proofing	Avoid valuable fixed units and or interior fittings in flood endangered floors	0.246 (0.191,0.301)	€2,389 per building (€800,€7250)
Dry flood-proofing	Mobile barriers to prevent water entering the building	0.128 (0.082,0.174)	€471 per building (€265,€845)

Table SI3. Calibrated parameters of the Generalized Pareto distributions of subjective flood occurrence perceptions

	Parameter Estimates		
	K	σ	θ
		Subjective flood probabilities	
Austria	1.89	0.32	0
Belgium	1.91	0.29	0
Germany	1.85	0.41	0
Denmark	1.64	1.31	0
France	1.66	1.21	0
Spain	1.74	0.75	0
Finland	1.86	0.38	0
Ireland	1.76	0.64	0
Italy	1.82	0.47	0
The Netherlands	2.04	0.15	0
Sweden	1.66	1.16	0
The United Kingdom	1.90	0.31	0
Bulgaria	1.77	0.7	0
Czech Republic	1.8	0.64	0
Estonia	1.77	0.72	0
Greece	1.76	0.72	0
Croatia	1.76	0.73	0
Hungary	1.8	0.65	0
Lithuania	1.77	0.71	0
Luxembourg	1.8	0.64	0
Latvia	1.78	0.69	0
Poland	1.78	0.69	0
Portugal	1.76	0.73	0

Romania	1.78	0.69	0
Slovenia	1.79	0.66	0
Slovakia	1.8	0.64	0
Subjective flood impacts	-0.2	1	0.1

Table SI4. Calibrated parameters of the Generalised Pareto distributions

	Scenario 1			**Scenario 2**			**Scenario 3**		
	K	σ	θ	K	σ	θ	K	σ	θ
wet flood-proofing	1.91	0.191	0.096	1.61	0.61	0	3.46	0.35	0.18
dry flood-proofing	0.44	0.044	0.022	1.14	0.114	0.057	1.31	0.13	0.07

Notes: Risk reduction perception distributions are calibrated using survey data from: [a] Poussin et al.(5) ; [b] Kreibich et al.(17) ; [c] Bubeck et al.(16) .

SI References

1. DEFRA. Flood risk and insurance: A roadmap to 2013 and beyond final report of the flood insurance working groups pb 13684. London: Department for Environment, Food and Rural Affairs.
2. European Comission. Green paper on the insurance of natural and man-made disasters (communication no. Com(2013) 213 final). Strasbourg: European Commission.
3. Michel-Kerjan E, Kunreuther H. Redesigning flood insurance. Science, 2011; 333:408-9.
4. Paudel Y, Botzen WJW, Aerts JCJH. A comparative study of public-private catastrophe insurance schemes: Lessons from current practices. Geneva Papers on Risk and Insurance, 2012; 37:257-85.
5. Poussin JK, Botzen WJW, Aerts JCJH. Stimulating flood damage mitigation through insurance: An assessment of the french catnat system. Environmental Hazards, 2013; 12:258-77.
6. Schwarze R, Wagner GG. The political economy of natural disaster insurance: Lessons from the failure of a proposed insurance scheme in germany. Environmental Policy and Governance, 2007; 17 (6):403-15.
7. Feyen L, Dankers R, Bódis K et al. Fluvial flood risk in europe in present and future climates. Climatic Change, 2012; 112:47-62.
8. Rojas R, Feyen L, Watkiss P. Climate change and river floods in the european union: Socio-economic consequences and the costs and benefits of adaptation. Global Environmental Change, 2013; 23 (6):1737-51.
9. Paudel Y, Botzen WJW, Aerts JCJH. Estimation of insurance premiums for coverage against natural disaster risk: An application of bayesian inference. Natural Hazards and Earth Schemes Science, 2013; 13:737-54.
10. Paudel Y, Botzen WJW, Aerts JCJH et al. Risk allocation in a public-private catastrophe insurance system: An actuarial analysis of deductibles; stop-loss; and premium. Journal of Flood risk Management, 2015; 8 (2):116-34.
11. Hudson P, Botzen WJW, Feyen L et al. Incentivising flood risk adaptation through risk based insurance premiums: Trade-offs between affordability and risk reduction. Ecological Economics, 2016; 125:1-13.
12. Savage LJ. The foundation of statistics. New York: John Wiley; 1954.
13. Botzen WJW, Aerts JCJH, van den Bergh JCJM. Dependence of flood risk perceptions on socioeconomic and objective risk factors. Water Resources Research, 2009; 45 (10).
14. Botzen WJW, Kunreuther H, Michel-Kerjan E. Divergence between individual perceptions and objective indicators of tail risks: Evidence from floodplain residents in new york city. Judgment and Decision Making, 2015; 10:365-85.
15. GDV. Naturgefahrenreport 2013 - die schaden-chronik der deutschen versicherer mit zahlen,stimmen und ereignissen. German insurance association (gdv) (2013), available at: Http://bit.Ly/1i7ich2. 2013.

16. Bubeck P, Botzen WJW, Kreibich H et al. Long-term development and effectiveness of private flood-risk reductions: An analysis for the german part of the river rhine. Natural Hazards and Earth Schemes Science, 2012; 12:3507-18.
17. Kreibich H, Thieken AH, Petrow T et al. Flood loss reduction of private households due to building precautionary measures- lessons learned from the elbe flood in august 2002. Natural Hazards and Earth Schemes Science, 2005; 5:117-26.
18. Hudson P, Botzen WJW, Kreibich H et al. Evaluating the effectiveness of flood damage risk reductions by the application of propensity score matching. Natural Hazards and Earth Schemes Science, 2014; 14 (1731-1747).
19. Kron W. Flood risk = hazard • values • vulnerability. Water International, 2005; 30 (1):58-68.
20. Jongman B, Hochrainer-Stigler S, Feyen L et al. Increasing stress on disaster-risk finance due to large floods. Nature Climate Change, 2014; 4:264-8.
21. Winsemius HC, Aerts JCJH, van Beek LPH et al. Global drivers of future river flood risk. Nature Climate Change 2016; 6 (4):381-85.
22. Winsemius HC, van Beek LPH, Jongman B et al. A framework for global river flood risk assessments. Hydrology and Earth System Sciences, 2013; 17 (5):1871–92.
23. De Moel H, Aerts JCJH. Effect of uncertainty in land use, damage models and inundation depth on flood damage estimates. Natural Hazards, 2011; 58 (1):407-25.
24. Smith DI. Flood damage estimation – a review of urban stage-damage curves and loss functions. Water SA 1994; 20 (3):231-8.
25. Schwarze R, Schwindt M, Weck-Hannemann H et al. Natural hazard insurance in europe: Tailored responses to climate change are needed. Environmental Policy and Governance, 2011; 21 (1):14-30.
26. Surminski S, Eldridge J. Flood insurance in england: An assessment of the current and newly proposed insurance scheme in the context of rising flood risk. Journal of Flood Risk Management, 2015.
27. Mas-Colell A. Microeconomic theory. New York: Oxford University Press; 1995.
28. Pakdel-Lahiji N, Hochrainer-Stigler S, Ghafory-Ashtiany M et al. Consequences of financial vulnerability and insurance loading for the affordability of earthquake insurance systems: Evidence from iran. The Geneva Papers on Risk and Insurance – Issues and Practice, 2015; 40 (2):295-315.
29. Poussin JK, Bubeck P, Aerts JCJH et al. Potential of semi-structural and non-structural adaptation strategies to reduce future flood risk: Case study for the meuse Natural Hazards and Earth Schemes Science, 2012; 12 (3455-3471).
30. Penning-Rowsell EC, Pardoe J. Who benefits and who loses from flood risk reduction? Environmental and Planning C: Government and Policy, 2012; 30:448-66.
31. Raschky PA, Schwarze R, Schwindt M et al. Uncertainty of governmental relief and the crowding out of flood insurance. Environmental Resource Economics, 2013; 54:179-200.
32. Hudson P. A comparison of definitions of affordability for flood risk adaption measures: A case study of current and future risk-based flood insurance premiums in europe. Mitigation and Adaptation Strategies for Global Change, 2018; 23 (7):1019-38.
33. Clementi F, Gallegati M. Physica A, 2005; 350:427.
34. Di Matteo T, Aste T, Hyde ST. In: The physics of complex structures. Amsterdam: IOS Press; 2005; p. 435.
35. Souma W. Universal structure of the personal income distribution. Fractals 2001; 9:293.
36. Hudson P, Botzen WJW, Czajkowski J et al. Risk selection and moral hazard in natural disaster insurance markets: Empirical evidence from germany and the united states. Land Economics, 2017; 93 (2):179-208.
37. Kreibich H, Christenberger S, Schwarze R. Economic motivation of households to undertake private precautionary measures against floods. Natural Hazards and Earth Schemes Science, 2011; 11:309-21.
38. Ward PJ, Jongman B, Weiland SF et al. Assessing flood risk at the global scale: Model setup, results, and sensitivity. Environmental Research Letters, 2013; 8 (4):044019.
39. Bubeck P, Botzen WJW, Aerts JCJH. A review of risk perceptions and other factors that influence flood mitigation behavior. Risk Analysis, 2012; 32 (9):1481-95.

40. Tversky A, Kahneman D. Advances in prospect theory: Cumulative representation of uncertainty. Journal of Risk and Uncertainty 1992; 5 (4):297-323.
41. Haer T, Botzen WJW, de Moel H et al. Integrating household risk mitigation behavior in flood risk analysis: An agent-based model approach. Risk Analysis, 2016.
42. Surminski S. Fit for purpose and fit for the future? An evaluation of the uk's new flood reinsurance poolResources for the Future, 2017.
43. European Comission. Insurance of weather and climate-related disaster risk: Inventory and analysis of mechanisms to support damage prevention in the eu. Luxembourg: Publications Office of the European Union, 2017.
44. DEFRA. Developing the evidence base for flood resistance and resilience: Summary report. London, UK: Environment Agency and DEFRA.
45. Surminski S, Aerts JCJH, Botzen WJW et al. Reflection on the current debate on how to link flood insurance and disaster risk reduction in the european union Natural Hazards 2015; 79 (3):1451-79.
46. Kunreuther H, Michel-Kerjan E. At war with the weather: Managing large scale risks in a new era of catastrophes. Cambridge, MA: MIT Press; 2009.
47. Kousky C, Kunreuther H. Addressing affordability in the national flood insurance program. Journal of Extreme Events, 2014; 1 (1):1450001.
48. Michel-Kerjan E, Czajkowski J, Kunreuther H. Could flood insurance be privatised in the united states? A primer. The Geneva Papers on Risk and Insurance Issues and Practice, 2015; 40 (2):179-208.
49. Kunreuther H. Encouraging adaptation to flood risk: The role of the national flood insurance program. In: Wharton Working Papers. Series Encouraging adaptation to flood risk: The role of the national flood insurance program. Philadelphia, USA: Wharton, University of Pennsylvania; 2017.
50. Golnaraghi M, Surminski S, Schanz K. An intergrated appraoch to managing extreme events and cliamte risks. . Zurich: The Geneva Assocaition.
51. The Geneva Association. Climate change and the insurance industry: Taking action as risk managers and investors perspectives from c-level executives in the insurance industryThe Geneva Association.
52. Paleari S. Disaster risk insurance: A comparison of national schemes in the eu-28. International Journal of Disaster Risk Reduction, 2019; 35:101059.
53. Botzen, Bouwer LM, Scussolini P et al. Integrated disaster risk management and adaptation. In: R Mechler; LM Bouwer; T Schinko et al., editors Loss and damage from climate change: Concepts, methods and policy options. Cham: Springer International Publishing; 2019; p. 287-315.
54. Linnerooth-Bayer J, Surminski S, Bouwer LM et al. Insurance as a response to loss and damage? In: R Mechler; LM Bouwer; T Schinko et al., editors Loss and damage from climate change: Concepts, methods and policy options. Cham: Springer International Publishing; 2019; p. 483-512.
55. Unterberger C, Hudson P, Botzen WJW et al. Future public sector flood risk and risk sharing arrangements: An assessment for austria. Ecological Economics, 2019; 156:153-63.
56. OECD. Financial management of flood risk. Paris.
57. McAneney J, McAneney D, Musulin R et al. Government-sponsored natural disaster insurance pools: A view from down-under. International Journal of Disaster Risk Reduction, 2016; 15:1-9.
58. Kunreuther H. Disaster mitigation and insurance: Learning from katrina. Ann. Am. Acad. Pol. Soc. Sci.,, 2006; 604:208–27.
59. Kunreuther H, Pauly M. Rules rather than discretion: Lessons from hurricane katrina. Journal of Risk and Uncertainty, 2006; 33 (1):101-16.
60. Kunreuther H. The role of insurance in reducing losses from extreme events: The need for public-private partnerships. The Geneva Papers on Risk and Insurance Issues and Practice, 2015; 40:471.
61. Atreya A, Hanger S, Kunreuther H et al. A comparison of residential flood insurance markets in 25 countries. In: Wharton Working Papers. Series A comparison of residential flood insurance markets in 25 countries. Philidelphia, Pennsylyania: University of Pennsylvania; 2015.
62. Zurich Flood Risk Alliance. Measuring flood resilience – our approach. Zurich: Zurich Foundation, 2016.

63. Surminski S, Thieken A. Promoting flood risk reduction: The role of insurance in germany and england. Earth's Future, 2017; 5:979-1001.
64. UNISDR. Global assessment report on disaster individual flood protection. Revealing risk, redefining development. Geneva, Switerland, 2011.
65. National Research Council. Affordability of national flood insurance program premiums: Report 1. Washington, DC: National Research Council.
66. Zhao W, Kunreuther H, Czajkowski J. Affordability of the national flood insurance program: Application to charleston county, south carolina. Natural Hazards Review, 2016; 17 (1):1-14.
67. Hochrainer-Stigler S, Lorant A. Evaluating partnerships to enhance disaster risk management using multi-criteria analysis: An application at the pan-european level. Environmental Management, 2018; 61 (1):24-33.
68. Schanz K. Understanding and addressing global insurance protection gaps. Zurich, CH: The Geneva Assocation
69. Insurance Europe. Insurance and natural catastrophes 2018 [cited 2018 15.11.2018].
70. Raschky PA, Weck-Hannemann H. Charity hazard—a real hazard to natural disaster insurance? Environmental Hazards, 2007; 7 (4):321-9.
71. World Bank. Chapter 8 –the french experience on disaster risk management, improving the assessment of disaster risks to strengthen financial resilience. In. Washington D.C.; 2012.
72. Flood Re. How are the premiums set for ceded policies to the scheme? 2018 [cited 2018 27th November].
73. Hanger S, Linnerooth-Bayer J, Surminski S et al. Insurance, public assistance, and household flood risk reduction: A comparative study of austria, england, and romania. Risk Analysis, 2018; 38 (4):680-93.
74. Insurance Europe. Natcat chart — property insurance, private lines 2018 [cited 2018 15.11.2018].
75. Ghetu D. Nat cat – the insurance gap challenge. In: ICAR. Series Nat cat – the insurance gap challenge. Bucharest, Romania; 2016.
76. Surminski S. Fit for the future? An assessment of flood insurance in ireland. London, UK: Grantham Research Institute on Climate Change and the Environment.
77. Maccaferri S, Carboni J, Campolongo F. Natural catastrophes: Risk relevance and insurance coverage in the eu. Ispra Italy: Joint Research Centre.
78. Seifert-Dähnn I. Insurance engagement in flood risk reduction – examples from household and business insurance in developed countries. Nat. Hazards Earth Syst. Sci., 2018; 18 (9):2409-29.
79. O'Neill J, O'Neill M. Social justice and the future of flood insurance. York, UK.
80. Gizzi FT, Potenza MR, Zotta C, 35-61. The insurance market of natural hazard risks for residential properties in italy. Open Journal of Earthquake Research,, 2016; 5:35-61.
81. Thieken AH, Kienzler S, Kreibich H et al. Review of the flood risk management system in germany after the major flood in 2013. Ecology & Society, 2016; 21 (2):51.
82. European Comission. Study to support the evaluation of the eu adaptation stratergy, summaryEuropean Comission.