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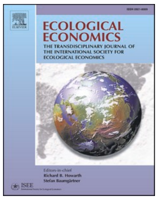

Charity hazard and the flood insurance protection gap: An EU scale assessment under climate change

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ABSTRACT

The flood insurance protection gap, the level of uninsured flood risk, is a problem faced by many European countries and is expected to increase due to climate change. In some countries a cause of low demand for flood insurance is the crowding out of private insurance uptake due to the anticipation of government compensation for uninsured damage, a phenomenon known as charity hazard. This study applies a partial equilibrium model of flood insurance markets to explore the extent of charity hazard and the insurance protection gap for EU-countries until 2050. For this analysis, we apply an expected utility framework with insurance purchase decision functions that capture the probability, ambiguity and extent of government compensation. By accounting for country-level insurance systems and government compensation types, as well as regional flood risk, we aim to assess how charity hazard develops under different conditions. The extent of charity hazard decreases with uncertainty of government compensation, as well as with higher flood risk. Considering current and future conditions, the highest impact of charity hazard is observed in regions of Germany and Italy. The projected insurance protection gap is highest in Germany, followed by Spain, Poland and Italy, and is expected to grow towards 2050.

1. Introduction

Climate change and socio-economic development is expected to cause a higher risk of riverine flooding in many regions across Europe (Alfieri et al., 2018). Insurance is an important adaptation mechanism to cope with increasing flood risk as it reduces high reconstruction costs of an individual's property after a flood through offering manageable annual premiums (Botzen et al., 2009). A challenge for the functioning of flood insurance markets is low demand for coverage, which may hamper the ability of insurance to spread risk and limit the costs imposed by floods. In countries where flood insurance is optional, the decision to purchase insurance coverage is influenced by many factors, including budget constraints (Kousky and Kunreuther, 2014), low flood risk perceptions of households (Kunreuther, 1984), and anticipated government compensation in the case a flood occurs (Browne and Hoyt, 2000). This study will focus on the latter. In particular, we seek to gain insight into the impact of unconditional government disaster relief on flood insurance demand on an EU-wide scale under future flood risk.

The Samaritan's dilemma describes how governments in modern welfare states are often implicitly obliged to provide disaster relief to those in need (Buchanan, 1975). The anticipation of disaster relief from governments logically reduces the incentive to purchase insurance coverage by individual households, a problem which has been termed “charity hazard” (Browne and Hoyt, 2000). In several EU-countries, including Italy, Austria and Germany, charity hazard is identified as a threat to the functioning of private flood insurance markets (Gizzi et al., 2016; Raschky et al., 2013; Schwarze and Wagner, 2007). Low demand for insurance leads to higher premiums as insurers are less able to spread risks effectively. This may further exacerbate the crowding out of insurance demand, as more households will opt for potential government aid. In order to preserve well-functioning private flood insurance markets it is therefore important to limit the decline of insurance uptake as a result of charity hazard.

Reliance on ex post government compensation can be undesirable for households, since there is no guarantee they will actually be compensated. The probability and extent of compensation often depends on

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political and economic circumstances. For example, (Garrett and Sobel, 2003) find that almost half of the US government's disaster relief payments are provided for political reasons and are not necessarily given where they are needed most. Higher disaster relief payments are found in election years, as well as in regions that are strategically important to the president. Besides creating ambiguity concerning the compensation for uninsured households after a disaster, the ambivalence of government aid may create uncertainty for public budget planning. The impact on government finances can be especially high when a natural disaster occurs during an economic crisis. Furthermore, the redirection of funds towards damage relief may reduce government spending for more productive purposes, such as welfare-enhancing expenses. These impacts may be limited if a government abstains from providing aid, or explicitly commits to a degree of compensation for uninsured households, as this enables the estimation of risk borne by the government, in which case it can better prepare for a flood disaster. Austria maintains such a system, where 25% of possible flood damages will be compensated by the government controlled catastrophe fund for certain, while the residual risk can be privately insured (Raschky et al., 2013).

Existing empirical and experimental evidence on charity hazard shows that the influence of government compensation for flood damage depends on the risk context, as well as the probability and extent of compensation (Andor et al., 2020). Negative impacts of government disaster compensation on insurance demand have been found by several studies, using datasets in the US, the Netherlands, Germany and Austria (Botzen and Van Den Bergh, 2012; Davlasheridze and Miao, 2019; Kousky et al., 2018; Landry et al., 2019; Raschky et al., 2013). These findings are consistent with (Brunette et al., 2013) who derive theoretically that government disaster relief decreases demand for insurance for risk-averse individuals in a model of insurance demand under ambiguous loss probabilities. However, against theoretical expectations, some studies find an increase of insurance demand resulting from anticipated government disaster relief in the US (Browne and Hoyt, 2000; Petrolia et al., 2013). This may be ascribed to endogeneinty of variables across empirical analyses of charity hazard (Kousky et al., 2018). For instance, in the study by Browne and Hoyt (2000), the unexpected finding may be attributed to endogeneity regarding the risk exposure of assessed households, which may positively impact both demand for insurance and the receipt of government relief. This particular cause of endogeneity is addressed in the empirical study by Davlasheridze and Miao (2019), who use precipitation data to separate the crowding out of insurance demand due to government aid from the increased risk awareness due to high levels of rainfall in the area. Moreover, Landry et al. (2019) detect a significant charity hazard effect in their empirical analysis and observe a 25% to 43% lower flood insurance uptake in high-risk coastal zones. Landry et al. (2019) limit endogeneity that may arise due to regional differences in government compensation policy, by using previously received flood damage compensation as an instrument for the expectation of damage relief.

Moreover, there is evidence suggesting that that the degree of charity hazard depends on the probability and extent of government compensation. For example, (Raschky and Weck-Hannemann, 2007) provide theoretical proof that demand for natural hazard insurance decreases as a result of higher levels of government disaster relief. Empirically, (Raschky et al., 2013) find that government compensation in Austria causes more crowding out of private insurance than in Germany because both countries implement ex post disaster relief differently. Whereas a limited extent of compensation is guaranteed in Austria (approximately 25% of damages), in Germany it can be considered ambiguous, as the extent of compensation is not formalized in legislation and is found to be influenced by political motives (Citlak and Wagner, 2001). Robinson et al. (2021) introduce ambiguity preferences and show theoretically that demand for insurance is higher when the probability of government compensation is ambiguous compared to when the probability is known by individuals, because on average they dislike the ambiguity of government compensation. Experimental results in Robinson et al. (2021) substantiate the existence of charity hazard when government compensation is partial but certain, and when the probability and extent of compensation is known, although they find little evidence to suggest that insurance demand decreases when government compensation is ambiguous. Osberghaus and Reif (2021) similarly confirm the crowding out of insurance demand when government compensation is certain but partial or uncertain but full. However, they find no difference in the extent of charity hazard between these two types of compensation. Finally, in an experimental setup (Brunette et al., 2013) find evidence of the crowding out of insurance uptake due to government compensation that is certain but partial, whereas no significant results were found for risky government compensation.

The goal of this study is to simulate charity hazard on a multinational scale and to examine its impact on the insurance protection gap, which is the societal degree of flood risk that is not covered by insurance. After theoretically deriving the extent of charity hazard under different compensation arrangements and risk preferences, we use a modelling approach to explore its implications under various conditions, including changing flood risk, and different flood insurance and government compensation policies. Performing this analysis on an EU-scale facilitates a comparison between different insurance and government compensation contexts, as well as a wide range of climatic conditions. For example, higher flood risk in Northern European countries may limit charity hazard compared to regions where flood risk is relatively low. The reason is that concern about flood damage and related demand for flood insurance may also be higher in areas with a higher flood risk. Moreover, the wide range of institutional arrangements regarding flood insurance and government compensation causes different degrees of charity hazard and the insurance protection gap between EU-countries. We account for these regional and country-level differences by including regional flood risk projections and allocating countries to stylized flood compensation systems. Using this approach we can isolate factors that impact flood insurance demand and by comparing such a diversity of flood compensation mechanisms in a setting of changing flood risk, we are able to assess which reforms of flood insurance arrangements are more suitable to cope with challenges posed by climate change. Moreover, by isolating factors of influence on the extent of charity hazard, this approach is able to prevent problems of endogeneity that are common in empirical studies.[1]

To carry out the described project we build upon theoretical proofs of flood insurance demand under uncertain government compensation, derived in Robinson et al. (2021), and the "Dynamic Integrated Flood Insurance" (DIFI) model developed by Hudson et al. (2019). We extend the theoretical proofs from Robinson et al. (2021) to the case of partial insurance coverage to match our simulation analysis with the DIFI model. These proofs show that the impacts of charity hazard on flood insurance demand depend on risk and ambiguity preferences, and on the extent and certainty of government compensation. Next, we augment the DIFI model to simulate the development of charity hazard and the insurance protection gap for all EU countries on a regional level under changing flood risk and different institutional arrangements. The DIFI model is used in earlier studies to identify optimal insurance market reforms for EU-countries (Hudson et al., 2019), for detecting regions where flood insurance markets may diminish as a result of climate change (Tesselaar et al., 2020b), and for assessing the impact of remote climate events on the functioning of EU flood insurance markets (Tesselaar et al., 2020a). These previous studies with the DIFI model however neglected government compensation for flood damage and the related charity hazard effect on flood insurance demand. Hence we

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[1] Instead of analyzing the complex reality of variables that determine charity hazard, as is done in most empirical research, this study reduces the complexity to several variables that influence charity hazard. Therefore, the estimated magnitude of charity hazard can be ascribed solely to these variables, and cannot be a result of unobserved variables.

extended the DIFI model in this study to enable the simulation of charity hazard. These extensions include adjusted decision functions, where households decide whether to purchase insurance coverage while taking into account the probability, ambiguity and extent of government compensation. For this, we categorize EU-countries into stylized insurance and government compensation systems based on a literature review. The results of this analysis improve the understanding of the extent of charity hazard in Europe, and may contribute to improving insurance market policies and flood risk management to cope with increasing challenges posed by climate change.

The following section of this article presents the theoretical foundations of charity hazard for different stylized types of government compensation for uninsured flood damage. Section 3 describes the DIFI model and the categorization of stylized types of flood insurance and government compensation. In Section 4 we present the model output, followed by a discussion of the method and the implications of the results in Section 5. Finally, in Section 6 we conclude the study and provide policy recommendations.

2. Theoretical framework of charity hazard

We derive our theoretical predictions (TP) according to Expected Utility Theory and the (Klibanoff et al., 2005) smooth model of decision making under ambiguity. The complete formal derivations are presented in Appendix A. Here we summarize the agents' decision making problem regarding insurance demand under various government compensation types and present the theoretical predictions that follow from this. The decision maker's choice variable in the theoretical framework is willingness-to-pay (WTP), which defines the premium payment that results in equality of expected utility with and without insurance (McIntosh et al., 2019).

Eq. (1) considers an individual who has initial wealth, W, and faces a loss, $L \in (0, W)$, with probability p, where $0 < p < 1$. Moreover, insurance coverage, $V = L\alpha$, may be purchased to protect against the potential loss, where $\alpha \in (0, 1)$ is the extent of coverage. The insurance premium is $P = L\alpha p\lambda$, and the loading factor is λ, where $\lambda = 1$ for actuarially fair insurance, $0 \leq \lambda < 1$ for subsidized insurance and $\lambda > 1$ for commercial (positively loaded) insurance. Utility, $U(\bullet)$, is a strictly increasing function defined on final wealth.

Furthermore, the individual anticipates compensation from the government, θ $(0 < \theta < 1)$, to pay for a proportion of the uninsured losses. In Eq. 1 the individual is assumed to know the probability of receiving government compensation (π), where $0 < \pi < 1$.

$$\begin{aligned} EU_{NI} &= \pi\{pU[W-(1-\theta)L]+(1-p)U[W]\}+(1-\pi)\{pU[W-L]+(1-p)U[W]\} \\ &= \pi\{pU[W-WTP-(1-\theta)(L-L\alpha)]+(1-p)U[W-WTP]\} \\ &+ (1-\pi)\{pU[W-WTP-(L-L\alpha)]+(1-p)U[W-WTP]\} \end{aligned} \tag{1}$$

The individual will choose to purchase insurance if and only if $WTP \geq P(\alpha)$. Otherwise, he/she chooses not to insure. Expected utility under no insurance coverage is defined according to expected utility in the case where the probability of government compensation is objectively known.

Based on this setup, two theoretical predictions can be derived according to an Expected Utility Theory analysis regarding the impact of the level and the probability of government compensation on WTP for partial insurance. The impact of the compensation level follows from government compensation crowding out demand for insurance, in line with the charity hazard hypothesis. The impact of the probability of receiving compensation is based on a risk averse individual, who will, out of two prospects with the same expected value, prefer the one with the lowest variance. First, increasing the level of government compensation negatively affects WTP for insurance, thereby decreasing insurance uptake assuming all else remains the same. Second, the probability of government compensation has a similar effect on WTP for insurance for risk averse individuals, assuming that the expected value of government compensation remains the same.

TP1. : Willingness-to-pay for partial insurance is negatively related to the level of government compensation.

TP2. : Willingness-to-pay for partial insurance is negatively related to the probability of government compensation for risk averse individuals, holding the expected value of government compensation constant.

Next we follow the (Klibanoff et al., 2005) smooth ambiguity model, and assume an individual with ambiguity preference, represented by the strictly increasing function, $\varphi(\bullet)$ defined over EU. Note that when ambiguity is present, there is a second-order probability distribution, $F(\overline{\pi})$, where $\overline{\pi}$ is a possible value of π.

In the Klibanoff et al. smooth ambiguity model value with no insurance (KMM_{NI}), $E(\bullet)$ is the expectation with respect to $F(\overline{\pi})$. In this framework, as well as in the following numerical simulation study, there are two considered objective probability distributions regarding $\overline{\pi}$, which is that either full government compensation is provided with certainty in the case of a flood, or no compensation is provided, as is shown in Eq. 2. The beliefs about the provision of government compensation are represented by $\sigma = (\sigma_1, \sigma_0)$, where σ_1 is the belief that the government will provide compensation for certain, while σ_0 is the belief that the government will not provide compensation after a flood for certain, and $\sigma_1 + \sigma_0 = 1$. Under ambiguous government compensation, the insurance purchase decision is made in accordance with the second order EU function, which we call the Klibanoff et al. smooth ambiguity model value (KMM):

$$\begin{aligned} KMM_{NI} &= \sigma_1\varphi\{U[W]\}+\sigma_0\varphi\{pU[W-L]+(1-p)U[W]\} = E\{\varphi\{EU(\overline{\pi})\}\} \\ &= \sigma_1\varphi\{U[W-WTP]\}+\sigma_0\varphi\{pU[W-WTP-(L-L\alpha)] \\ &+ (1-p)U[W-WTP]\} \end{aligned} \tag{2}$$

From the basic model with ambiguity presented in Eq. 2, two more theoretical predictions can be derived based on the Klibanoff et al. smooth ambiguity model. First, the WTP for partial insurance increases for higher levels of ambiguity aversion when government compensation is ambiguous. Second, for ambiguity averse individuals, the WTP for insurance is higher when government compensation is ambiguous compared to when the objective probability of government compensation is known by individuals. The intuition for this is that ambiguity aversion raises the WTP for elimination of risk since this also covers all ambiguity related to the risk. This last theoretical prediction holds when Eq. 1 is evaluated at $\pi = 0.5$ and $\theta = 1$, and Eq. 2 assumes $\sigma = (0.5,0.5)$ and ambiguity aversion.[2]

TP3. : Willingness-to-pay for partial insurance is positively related to the degree of ambiguity aversion when government compensation is ambiguous.

TP4. : Willingness-to-pay for partial insurance is higher under ambiguous full government compensation vs. risky full government compensation for ambiguity averse individuals.

3. Simulation approach

The previous section showed the theoretical proofs of the existence of charity hazard using a static conceptual model. This implies that features such as flood probability and impact, insurance premiums, and household wealth, are unchanged throughout the process, while the perceived likelihood of government compensation is adjusted to show how this affects insurance demand. While, a setup as such facilitates the isolation of the charity hazard effect, the extent of this effect depends on a complex interplay of factors that influence flood insurance demand and, for that reason, requires a modelling setup that captures these

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[2] According to Robinson et al. (2021), it also holds under the more general condition: $\sigma = \pi$.

aspects. By progressing on the Dynamic Integrated Flood Insurance (DIFI) model, this study is able to simulate charity hazard under different conditions, including regional flood risk, insurance premiums, household wealth, and different institutional arrangements regarding flood insurance and government compensation. In this section we describe the model setup that is used for the simulation of charity hazard and the flood insurance protection gap.

The description starts with the projection of flood risk, followed by the estimation of flood insurance premiums, and finally the simulation of household decision-making regarding insurance uptake. The simulation approach in this study extends upon the DIFI model, which is introduced in Hudson et al. (2019) and applied in Tesselaar et al. (2020b, 2020a). We refer to these studies for a detailed description of model components that are introduced there, while in this section we explain in detail the innovations that were developed for this study. The most notable novelties in this study are the introduction and allocation of stylized types of government compensation and the introduction of these types of compensation in the expected utility framework of the insurance purchase decision. Moreover we explain the application of households' ambiguity preferences, and the contribution of charity hazard to the insurance protection gap.

3.1. Flood risk module

The flood risk module uses climate- and socio-economic input data to estimate “Expected Annual Damage” (EAD) and its variance, for households in high-risk areas, and for periods up to 2050. These variables are used, at a later stage, to determine insurance premiums and subjective flood risk of households.

The current version of the DIFI model (DIFI 2.1) uses input data derived from the global flood risk model GLOFRIS (Ward et al., 2017; Winsemius et al., 2016) to calculate EAD. In particular, for this purpose the DIFI model projects flood risk by using flood damage estimates for several occurrence probabilities, or return periods. To simulate these damage estimates, GLOFRIS uses past data and future projections of flood hazard, exposure and vulnerability. Future flood risk projections are simulated based on climatic- and socio-economic scenarios in the form of RCP-SSP combinations. A “Representative Concentration Pathway” (RCP) predicts the level of future greenhouse gasses accumulated in the atmosphere, whereas a “Shared Socioeconomic Pathway” (SSP) forecasts population growth and economic development. The main analysis in this study applies a moderate future flood risk scenario RCP4.5-SSP2, while we include a broader range of future flood risk developments as a sensitivity analysis in Appendix B. Furthermore, for the estimation of EAD, the DIFI model takes into account the regional flood protection standards in place, which are derived from the FLOPROS database (Scussolini et al., 2016). As described in detail in Scussolini et al. (2016) this database is constructed using regional information on implemented or planned protection standards, or if this is not available, by inferring protection standards based on hazard-modelling and the relationship between per capita wealth and protection.

At this stage, we concentrate the analysis on areas at high risk of flooding, which we define as areas where a flood is expected to occur at least once every hundred years. These high-risk areas change over time, as the estimated area affected by a 1/100 year flood is simulated to develop according to projected climate change. For example, increases in peak river discharges as a result of climate change also increase potentially inundated areas during a flood event in future periods. High-risk areas are targeted because much of the debate about flood insurance policies focusses specifically on households located in these areas. For example, in the US, the 1/100 year floodplains are designated as “base flood zones” by FEMA (Federal Emergency Management Agency). Insurance uptake is mandatory for households located in these flood risk-zones that have a mortgage from a federal lending institution (Dixon et al., 2018). In the UK, the flood insurance system is designed to ensure affordability of coverage in high risk areas (Penning-Rowsell et al., 2014), which are demarcated as 1/75 year floodplains (Environmental Agency, 2009).

Finally, flood risk estimates are aggregated to the NUTS2-level,[3] which is the geographical level used for most of the remaining analyses. A detailed explanation of the simulation used to estimate flood risk is included in Appendix B.1.

3.2. Types of flood insurance systems and government disaster relief

The annual expected damage and its variance are used to simulate flood insurance premiums until 2050. For this, countries are allocated to one of several stylized insurance systems, which are described by (Hudson et al., 2019) and partly based on (Paudel et al., 2013) and (Paudel et al., 2015). The stylized insurance systems are designed to capture certain essential differences in national insurance arrangements that exist between EU countries. For example, flood insurance uptake may be voluntary or mandatory, premiums may be risk-based or independent of individual risk. By using stylized categories of insurance arrangements, the analysis in this study can identify certain characteristics of flood insurance that are better able to cope with challenges posed by climate change. The allocation of countries into the stylized categories of insurance systems follows Hudson et al. (2019), who describe the details of these systems. However, some changes have been made in accordance with an in-depth review of national flood insurance arrangements, which is included in Appendix D. Fig. 1, panel A, displays the allocation of EU-countries into the stylized categories of insurance systems. We classify four flood insurance types based on existing arrangements within the EU. In the voluntary system, uptake of coverage is optional, premiums are risk-based and reinsurance coverage is supplied by the private market. The semi-voluntary system is similar, except insurance coverage is mandatory for most households, as it may be a mortgage requirement or included in general homeowner insurance policies. The solidarity system maintains full cross-subsidization of flood risk, which is achieved by premiums that are insensitive to risk and mandatory insurance uptake for all. The public-private-partnership (PPP) is based on the system applied in the UK, where premiums are risk-sensitive up to a threshold, after which excess risk is shared with low-risk policyholders. The government is involved as a reinsurer, which guarantees low prices for reinsurance coverage, and uptake of insurance is also a mortgage requirement.

Besides multiple stylized insurance systems, we identify different forms of government disaster aid across EU-countries. These different forms amount to variations in the probability and extent of compensation for uninsured households, and ultimately affect the household's decision to purchase insurance, which is described in the following section. Fig. 1, panel B, displays a map where each country is allocated to a stylized type of government disaster relief. This categorization is based on an extensive literature review, a summary of which is shown in Appendix D. In panel B of Fig. 1, countries shown in light blue are found to maintain insurance uptake requirements to some extent. Although these countries may still provide ex post disaster aid to uninsured households, the impact of this provision on insurance demand is limited, which means that it is of lower relevance for this study. Countries highlighted in red generally do not provide disaster relief for uninsured households. Austria, the only country shown in dark blue, is representative of a system where the government provides certain partial compensation, meaning that a limited degree of compensation is guaranteed after a flood. For Austria, the extent of compensation is approximately 25% of damage caused by flooding. Finally, countries shown in pink are where disaster relief has historically often been made

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[3] The NUTS regions (nomenclature of territorial units for statistics) is a hierarchical system for dividing up economic territories of the EU, where NUTS2 are basic regions for the application of regional policies (Eurostat).

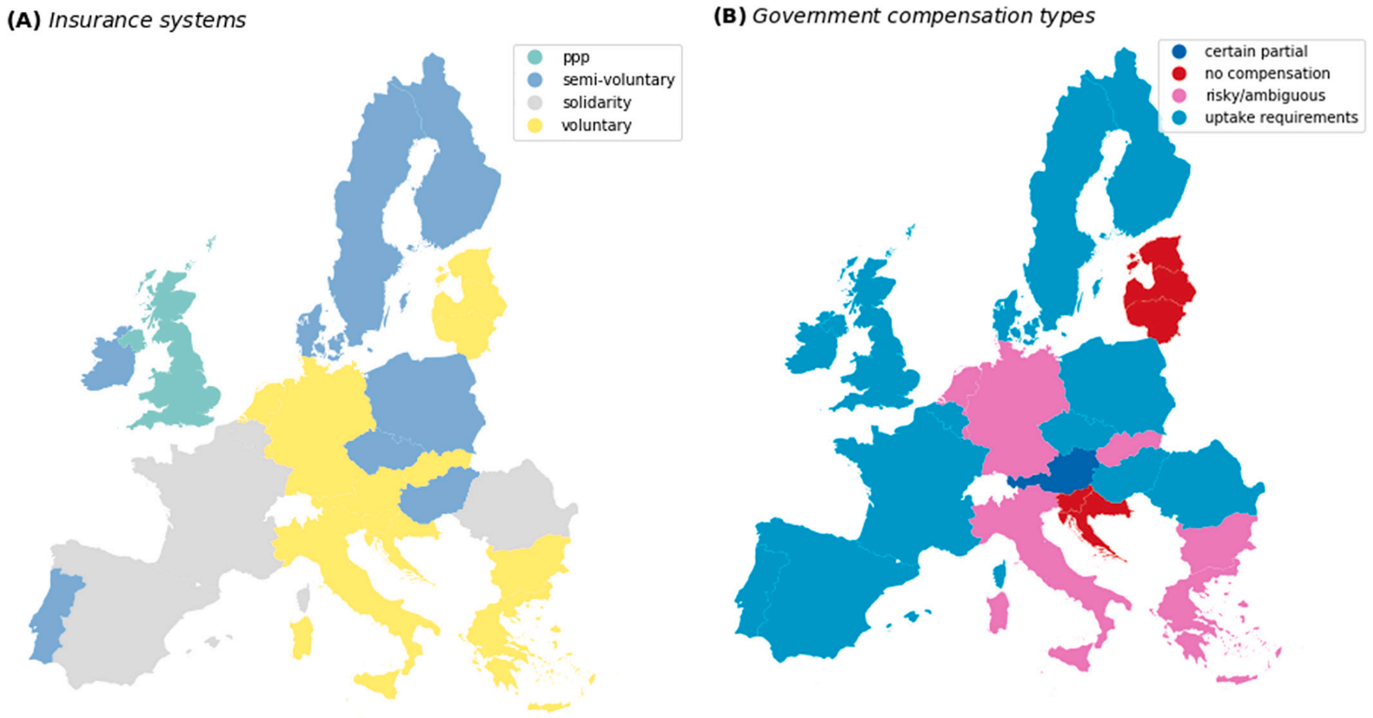

Fig. 1. (A) Allocation of EU-countries and the UK into stylized insurance system categories. In the voluntary system insurance uptake is optional, premiums are risk-based, and reinsurance is offered by the private market; the semi-voluntary system is similar except uptake is mandatory for some, for example because it is a mortgage requirement; in the solidarity system uptake is mandatory for all and premiums are unconnected to risk; in the public-private partnership (PPP) uptake is mandatory, premiums are partly risk-based, and reinsurance is provided by a public institution. (B) Categorization of types of government disaster aid in EU-countries and the UK. Countries shown in light blue maintain insurance uptake requirements, meaning that ex post government compensation cannot affect the insurance purchase decision for many individuals. Countries shown in red do not provide disaster relief for uninsured households. Austria, shown in dark blue, maintains a system where the government provides compensation for certain, but to a limited extend (25% of the losses). Countries shown in pink are where the probability of receiving disaster compensation for uninsured households is risky or ambiguous. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

available, while no explicit obligation, both in terms of probability and extent of compensation, is stated by governments. Therefore, households may regard disaster relief in these countries as risky or ambiguous, as defined in Section 2. In accordance with the theoretical predictions, in the model setup we assume full compensation under the stylized risky/ambiguous systems. While the amount of compensation may vary according to economic and political conditions, anecdotal evidence presented in Appendix D suggests that the amount of compensation in these systems often fully covers the uninsured damage. Moreover, the probability, or belief of the probability of receiving full compensation, is assumed fixed at 0.5 in the risky and ambiguous public compensation systems. Although in reality the probability of compensation may differ from this assumption, this simplification allows us to isolate the impact of ambiguity regarding the probability of receiving disaster aid. The following section describes in detail how each type of government compensation affects the insurance purchase decision of households.

The current analysis is concentrated on countries where uptake is voluntary because anticipation of government compensation by households does not impact demand for flood insurance in countries where coverage is mandatory.[4] A detailed description of the simulation of flood insurance premiums is included in Appendix B.2.

3.3. Household behavior module

The estimated flood risk and insurance premiums are used in the household behavior module, where household decision-making concerning insurance uptake is simulated. This decision function is performed for all households in high-risk areas per NUTS2-region and is repeated for each time-step. Each modelled household faces a budget constraint, where it is assumed to not purchase insurance coverage when the premium is deemed unaffordable. To assess this, for each iteration the household's income is drawn randomly from a log-normal income distribution on country-level, which is simulated to change according to projected GDP-growth in the considered SSP-scenario. Insurance is deemed unaffordable when the premium would cause a household's poverty-adjusted disposable income to descent below the poverty line, which is set at 60% of national median income.

$$E(U)_{certain} = \begin{cases} EU_{NI} = pU[W-(1-\Theta)L] + (1-p)(U[W]) \\ EU = pU[W-0.15L-P] + (1-p)U[W-P] \end{cases} \tag{3}$$

If insurance is affordable, a household's decision to purchase coverage is simulated using an expected utility maximization approach. As theoretically proven in Section 2, the choice to purchase insurance is dependent on whether a household anticipates government aid after a flood. Since the extent that government compensation impacts the decision to purchase insurance is dependent on the certainty and amount of relief, we simulate this choice for the stylized forms of ex post government support that exist in EU-countries, as presented in Fig. 1B. Eq. 3 expresses the insurance purchase decision function for a situation where the government is explicit about compensation for uninsured households. This is applicable for countries where governments do not provide compensation, such as Croatia, or provide compensation for certain to a limited extent, such as Austria. The decision framework consists of two separate expected utility functions, one with insurance coverage and one without, and the household chooses whichever outcome is higher. EU_{NI}

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[4] We refer to (Hudson et al., 2019) for a technical description of the other types of insurance systems.

shows the expected utility of not insuring, which is determined by the probability of a flood event (p) multiplied by the utility the household derives from its wealth (W) subtracted by the loss of wealth caused by the flood (L) and the extent of government compensation (Θ). This is added with the utility when no flood occurs, in which case the household maintains its wealth (W). *EU* shows the expected utility of purchasing insurance, where households pay only the deductible of 15% of damage when a flood occurs, plus the premium (P), which is also paid in the case no flood occurs. Since the insurance purchase decision is a yearly reoccurring choice, time discounting is of negligible importance and is therefore ignored in this function.

Many variables in Eqs. 3, 4 and 5 are similarly derived as in Hudson et al. (2019). The flood occurrence probability (p) and the flood loss (L) are individual perceptions of the probability and impact of flooding, which are calibrated using methods developed in (Hudson et al., 2019). The wealth (W) of individual households is determined as a fixed proportion of income, as indicated by (Eurostat, 2010). Finally, we apply a power utility function of the form $U(x)=x^r$, where x is the final wealth (W) across different states of nature, and r is the risk aversion parameter, which exhibits risk aversion for $r < 0$, risk neutrality for $r = 1$, and risk seeking behavior for $r > 1$. A utility function of this form expresses constant relative risk aversion (CRRA), and is commonly used to model risk aversion (Wakker, 2008). In order to compare outcomes across utility functions, where different types of government disaster relief are applied, we standardize the level of risk aversion at $r=0$. At this level of risk aversion the power utility function is replaced by a logarithmic function (Wakker, 2008), which is mathematically and philosophically justified to be used as a general utility function (Sheng, 1984). We provide a sensitivity analysis in Appendix C, where we show how insurance uptake changes for different values of risk aversion. It can be seen in Fig. C3 that demand for insurance falls for lower values of risk aversion (higher levels of r), while it increases rapidly for higher values of risk aversion (lower levels of r).

$$E(U)_{risky} = \begin{cases} EU_{NI} = p(\pi U[W] + (1-\pi)U[W-L]) + (1-p)(U[W]) \\ EU = pU[W - 0.15L - P] + (1-p)U[W-P] \end{cases} \tag{4}$$

Eq. 4 expresses the insurance purchase decision of households when government compensation of uninsured damage is considered risky. Consistent with TP2, we simplify the probability of receiving government compensation to 50% and coverage to 100% of damage. In Figs. C4 and C5 in Appendix C we present the sensitivity of insurance uptake to the probability and degree of government compensation of uninsured damages. It can generally be seen that insurance demand responds as expected (following TP1 and TP2) to the probability and extent of government compensation, i.e. insurance demand is lower for higher probabilities and amounts of government compensation. In Eq. 4, the probability of receiving government compensation (π) enters the utility function for not purchasing insurance EU_{NI}. In the case a flood occurs, households have a 50% chance of receiving government compensation and maintaining their wealth, or there is a 50% chance that the damage is not compensated.

$$E(U)_{ambiguous} = \begin{cases} EU_{NI} = \sigma\varphi\{(U[W])\} + (1-\sigma)\varphi\{(pU[W-L]) + (1-p)(U[W])\} \\ EU = \varphi\{pU[W-0.15L-P] + (1-p)U[W-P]\} \end{cases} \tag{5}$$

Eq. (5) captures the insurance purchase decision where uninsured households do not know the probability of receiving government compensation. Consistent with the theoretical model in Section 2 we assume that the belief of receiving government aid is $\sigma = (0.5,0.5)$, meaning households believe that both full and no compensation occur with a probability of 0.5. Ambiguity preferences in Eq. 5 are captured by φ and are applied similarly as risk preferences using a power ambiguity preference function of the form $\varphi(Z)=Z^{\nu}$, where Z is expected utility across the different beliefs about receiving disaster aid, and ν expresses ambiguity preferences. For the baseline scenario we allocate ambiguity preferences to modelled households in line with empirical results in (Dimmock et al., 2015), who find that 52% of individuals are ambiguity-averse, 38% ambiguity-seeking and 10% ambiguity-neutral, using a representative sample of the US population. In Figs. C1 and C2 in Appendix C we show the results of a sensitivity analysis where we test the impact of ambiguous compensation on insurance demand compared to risky compensation for different compositions of ambiguity preferences amongst the population.

3.4. Uncovered flood risk

After simulating the insurance uptake decisions we are able to assess the level of flood risk that is not covered by insurance, also known as the insurance protection gap. This statistic gives the potential annual public funds needed to cover uninsured damage when governments provide damage relief. We evaluate the insurance protection gap for the various stylized types of government disaster relief and are, therefore, able to assess which policy choice can limit uninsured risk. The insurance protection gap is determined by multiplying the EAD per capita with the uninsured population, which is the inverse of the penetration rate multiplied by the exposed population. The insurance protection gap is evaluated at country-level because the required disaster relief is often provided by national governments. The impact of the insurance protection gap on the government budget depends on the actual amount of damage compensated by governments. In the modelled certain partial compensation system this means that approximately 25% of flood risk is a burden for the public budget, while in the stylized risky or ambiguous compensation systems we assume that, on average, half of the projected annual damage is compensated by governments. However, actual compensation levels will fluctuate according to political incentives and economic conditions, but also the actual impact of flood disasters. This is because the insurance protection gap in terms of EAD gives an averaged view of the uninsured risk, as the risk of unlikely extreme events is spread out over time. Therefore, a single extreme flood event can cause a significantly higher degree of uninsured damage and, therefore, a potentially much higher impact on the government budget.

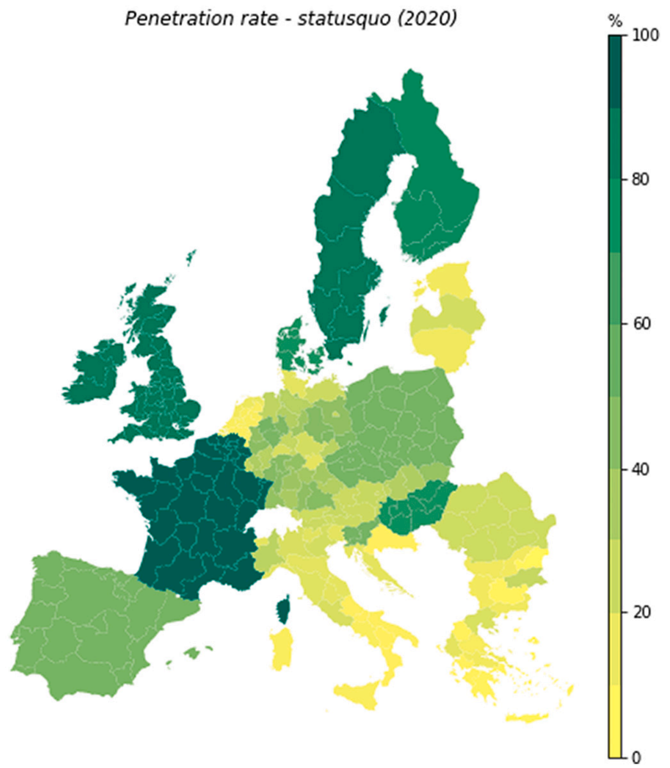
4. Simulation results

This section presents the output of the numerical simulation exercise. Firstly, the projections of insurance penetration rates are presented for current insurance arrangements and for different types of government disaster relief as displayed in Fig. 1. After this, the insurance protection gap is projected assuming that insurance systems remain unchanged.

Fig. 2 displays the modelled insurance penetration rates under current insurance arrangements in 2020. Countries where uptake requirements exist are shown to have fixed insurance penetration rates across NUTS2 regions. For countries where insurance uptake is voluntary, the simulation of penetration rates takes into account the type of ex post government compensation as shown in Fig. 1B. In Fig. 2 it can be seen that insurance penetration rates are generally lower in countries where uptake is optional, such as Germany, Italy and Greece, compared to countries where purchase requirements exist, such as Spain, France and Poland.

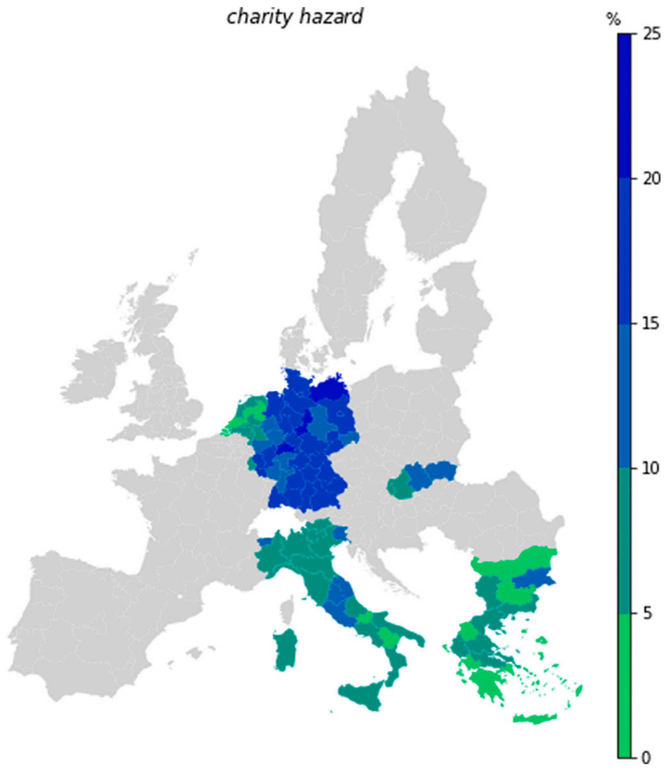
In Fig. 3 we present the extent of charity hazard by showing the projected difference in penetration rates between voluntary insurance systems in a hypothetical situation where there is no government compensation and one where the compensation is risky. Essentially, this depicts how much insurance penetration is lower due to households anticipating risky government assistance after a flood. Following TP2 in the theoretical model, the demand for insurance should decline with a higher degree and probability of government compensation. Therefore, insurance uptake should be higher under risky compared to no compensation. It can be seen that the largest decline in uptake occurs in certain regions in Germany, Slovakia and Italy, which is at the national level, respectively, 16.9%, 10.7% and 8.1%. An interesting observation is that regions that show the largest decline in uptake are where flood risk is relatively low. In regions where flood risk is higher, such as the Rhine and Elbe river basins, as well as regions in Central and Northern Italy, the risk awareness may be higher, but also the loss for households when there is no government support. Therefore, in Eqs. 3, 4 and 5 the flood probability (p) and the loss (L) are higher for these regions, which increases the potentially uncovered risk for households when not insured, making the purchasing of insurance more attractive despite potential government disaster relief. In other areas, such as Greece, Bulgaria and the Netherlands, the insurance penetration rate is very low in a hypothetical state of no government compensation, which means that it cannot decline much as a result of charity hazard. In the Netherlands, government flood protection standards are very high which explains the overall low insurance demand, while in Bulgaria unaffordability is limiting insurance demand, and Greece has generally low flood risk.

In Fig. 4 we present the projected difference in insurance uptake between risky and ambiguous government compensation for countries with voluntary flood insurance. This shows the effect derived in TP4, where it is proven that ambiguity regarding the probability of receiving government compensation for uninsured damage leads to higher demand for flood insurance for ambiguity averse individuals compared to a situation where this probability is known. Fig. 4 shows that when the probability and extent of government compensation is ambiguous, the penetration rate is equal or higher than a situation where the probability of receiving government compensation is objectively known by households. The extent of this difference depends largely on the level of flood risk in the area, which increases the degree to which risk averse households prefer insuring over not insuring. As was shown in Fig. 3, in high-risk areas more households will choose to insure despite the known probability of receiving government aid. Therefore, the impact of introducing ambiguity will be limited. On the other hand, in regions where flood risk is relatively low, such as regions in Germany further



Penetration rate - statusquo (2020)

Fig. 2. Insurance penetration rate in 2020 for existing insurance arrangements per country.



charity hazard

Fig. 3. Charity hazard. The difference in insurance demand between risky government compensation and no government compensation in 2020 for countries with voluntary insurance and ambiguous ex post government compensation.

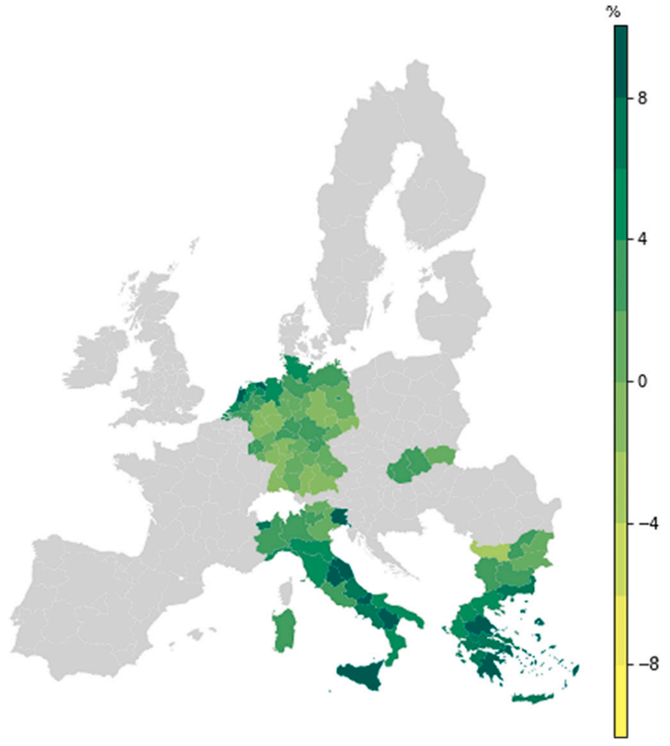


Fig. 4. The difference between ambiguous and risky government compensation in 2020 for countries with voluntary insurance and uncertain ex post government compensation.

from the Rhine and Elbe basins, or Italy south of the Po-basin, the choice whether to insure becomes more ambivalent, as uncovered losses are smaller. Therefore, introducing ambiguity can have a larger impact on insurance uptake.

The difference in insurance uptake between ambiguous and risky government compensation do not change significantly in projections for 2050. On average, for countries with voluntary flood insurance and ambiguous government compensation, projected insurance uptake is 3.7% higher for ambiguous compared to risky compensation in 2020, whereas this is 3.3% in 2050. What does have a significant impact on this difference are modelled ambiguity preferences. Fig. C1 in Appendix C shows similar results as Fig. 4, while using an alternative distribution of ambiguity preferences, where more modelled households are ambiguity averse and less are ambiguity seeking. As expected and in accordance with the theoretical proof in support of TP3, due to more occurrences of ambiguity aversion, the difference concerning insurance uptake between ambiguous and risky compensation becomes greater (9.9%). On the contrary, Fig. C2 shows a sensitivity analysis of ambiguity preferences where the majority of modelled households is ambiguity seeking and only a fraction of households is ambiguity averse. In this case, more households value ambiguous over risky government compensation, leading to 1% more demand for flood insurance under the risky compensation type.

In Fig. 5 we present insurance demand for each stylized type of government compensation, by focusing on Germany specifically. This is done because under current insurance arrangements ex post government compensation does not affect insurance uptake in most stylized insurance systems for EU countries. Germany provides an exemplary illustration as the voluntary insurance penetration under its current system is relatively high, while also showing much variation in regional flood risk levels. In Fig. 5 it can be seen that insurance uptake, on average, is highest when it is known that the government does not provide disaster relief after floods, which is followed by ambiguous, risky, and certain partial compensation respectively. Particularly interesting is that the penetration rate under certain partial compensation, where 25% of damages are compensated for certain, is, on average over the NUTS2 regions, approximately 1% lower than risky full compensation, which has a 50% probability of compensation. This result indicates that risk aversion, as implemented in the model, is consistent with TP2 in the theoretical foundation of this study, which points out that demand for insurance is negatively related to the probability of government compensation. Moreover, this model outcome is consistent with empirical findings in (Raschky et al., 2013).

As shown in this section, the insurance penetration may be relatively low as a result of insurance system policies in place and the degree of charity hazard. Low insurance uptake means there is an insurance protection gap, where a part of society is not covered by insurance. For uninsured households there is a need for alternative financing of flood damage, such as government disaster relief or private savings. Fig. 6 presents the uninsured annual flood risk for 2020 and 2050 on country level for current insurance systems and government compensation types. The level of uncovered flood risk is highest for Germany, followed by Spain, Poland and Italy. Furthermore, the level of uncovered flood risk is larger in 2050, which is a result of higher flood risk and insurance uptake that is not rising to the same extent as risk. It is also noteworthy that uncovered risk is expressed here as the uninsured expected annual flood damage, meaning that uninsured damage after a large flood event can be much higher than shown here.

The level of uninsured annual risk in the future is dependent on developments in climate- and socio-economic change. In Fig. 7 we display the projected insurance protection gap in 2050 for multiple flood risk scenarios, where the middle (orange) bar corresponds to the level of

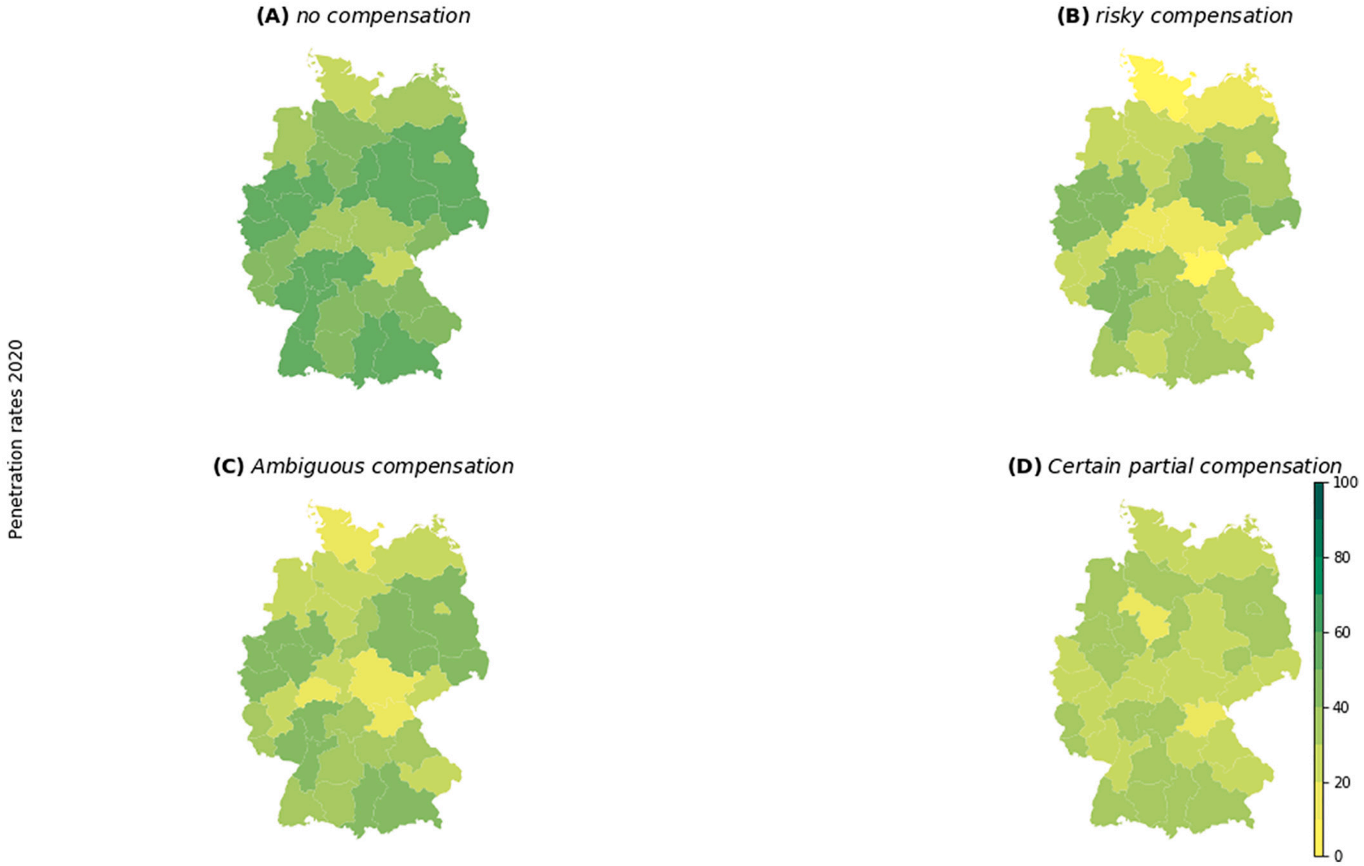


Fig. 5. Insurance penetration in 2020 under various forms of ex post government compensation in Germany.

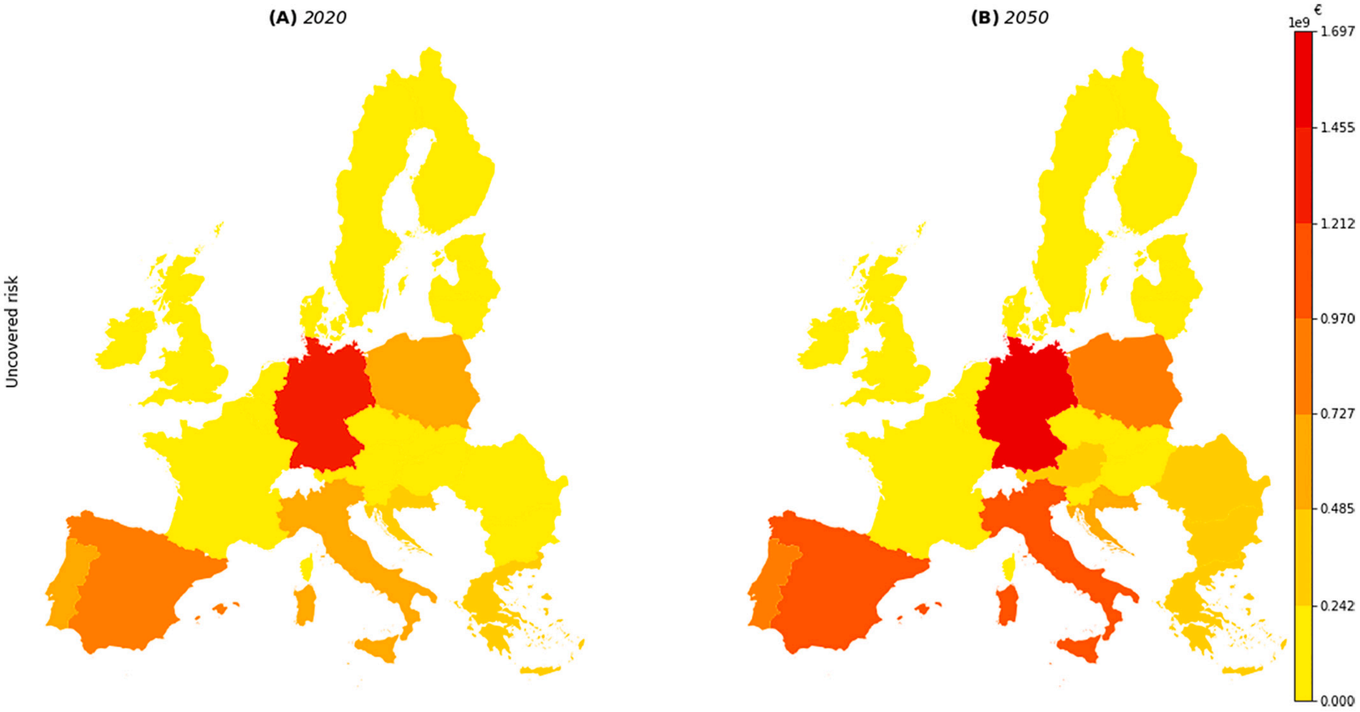


Fig. 6. Uninsured annual flood risk (in bln €/yr) per country under current insurance systems and government compensation arrangements for 2020 (A) and 2050 (B).

uninsured risk for RCP4.5-SSP2, as shown in Fig. 6B, while the left (blue) bar corresponds RCP2.6-SSP1, which is an optimistic scenario of low greenhouse gas concentration and sustainable economic growth, and the right (green) bar represents RCP8.5-SSP5, a pessimistic scenario of severe climate change and high but unsustainable economic growth. As expected, the insurance protection gap consistently rises for more severe projections of flood risk, because demand for insurance does not rise sufficiently to compensate the rising risk.

By changing the type of government compensation for flood damage, governments can stimulate insurance uptake and potentially reduce the level of uninsured risk. Fig. 8 displays the projected uninsured risk in 2050 for the different types of government compensation considered in this study, which are shown for countries that currently provide government compensation to some degree. The level of uninsured risk is related to the impact of charity hazard shown in Fig. 5, where certain partial government support is shown to cause the lowest insurance uptake, which causes the highest level of uninsured risk for Germany in Fig. 8. The uninsured risk declines due to higher insurance uptake under ambiguous, risky and no government compensation respectively. Besides this, the extent of the insurance protection gap will differ depending on actual or expected probabilities and amounts of compensation. This is because the demand for insurance is affected by the probability and extent of government compensation, as follows from a sensitivity analysis presented in Figs. C4 and C5 in Appendix C. The effects of charity hazard on uninsured risk are greatest for Germany, where the difference in uninsured annual risk between ambiguous compensation and a scenario of no compensation amounts to €360 million.

5. Discussion

5.1. Discussion of model uncertainty and sensitivity analysis

The model setup used for this study requires an extensive sensitivity analysis to observe how results and conclusions may change as a result of uncertain parameters and assumptions. Many of these parameters, such as uncertainty in risk and premium estimates, alternative utility functions, and different flood risk scenarios, are already tested in a sensitivity analysis supplementing Hudson et al. (2019), who find that the overall conclusions, that is the recommended flood insurance system per EU-country, is robust to these assumptions and parameters. The extension to the DIFI model that is developed and applied for the current study requires an additional sensitivity analysis to test whether the newly introduced assumptions and parameters behave predictably when changed, enabling the results to be interpretable and applicable for real-world circumstances. In Appendix C we present a sensitivity analysis of these variables, which include alternative flood risk scenarios, alternative compositions of ambiguity preferences amongst the population, different assumptions about risk preferences, and various probabilities and degrees of government compensation. The outcome of these sensitivity analyses are already discussed in relevant parts of the methods or results section to indicate their significance for the overall results. However, here we wish to summarize the performed sensitivity analysis and conclude that overall outcomes of this study are robust and behave as expected to the uncertain assumptions and parameters. Higher climate change scenarios lead to larger insurance protection gaps, more ambiguity aversion causes a higher degree of charity hazard, stronger risk aversion generates higher insurance uptake, and higher probabilities and amounts of government compensation causes more crowding out of demand for coverage.

The uncertainty of future flood risk and socio-economic development up to 2050 is considered by applying both an optimistic scenario (RCP2.6-SSP1) and a high flood risk scenario (RCP8.5-SSP5) in the analysis for the insurance protection gap presented in Fig. 8. The reason that we decided to focus on a single “middle-of-the-road” scenario (RCP4.5-SSP2) for the main analysis on charity hazard is that the impact of alternative flood risk scenarios on these projections is found to be limited. Therefore, discussing these results would create additional complexity in the presentation of results, while the added benefit would be insignificant.

To investigate the impact of charity hazard on future flood insurance penetration and the insurance protection gap the DIFI model is adapted

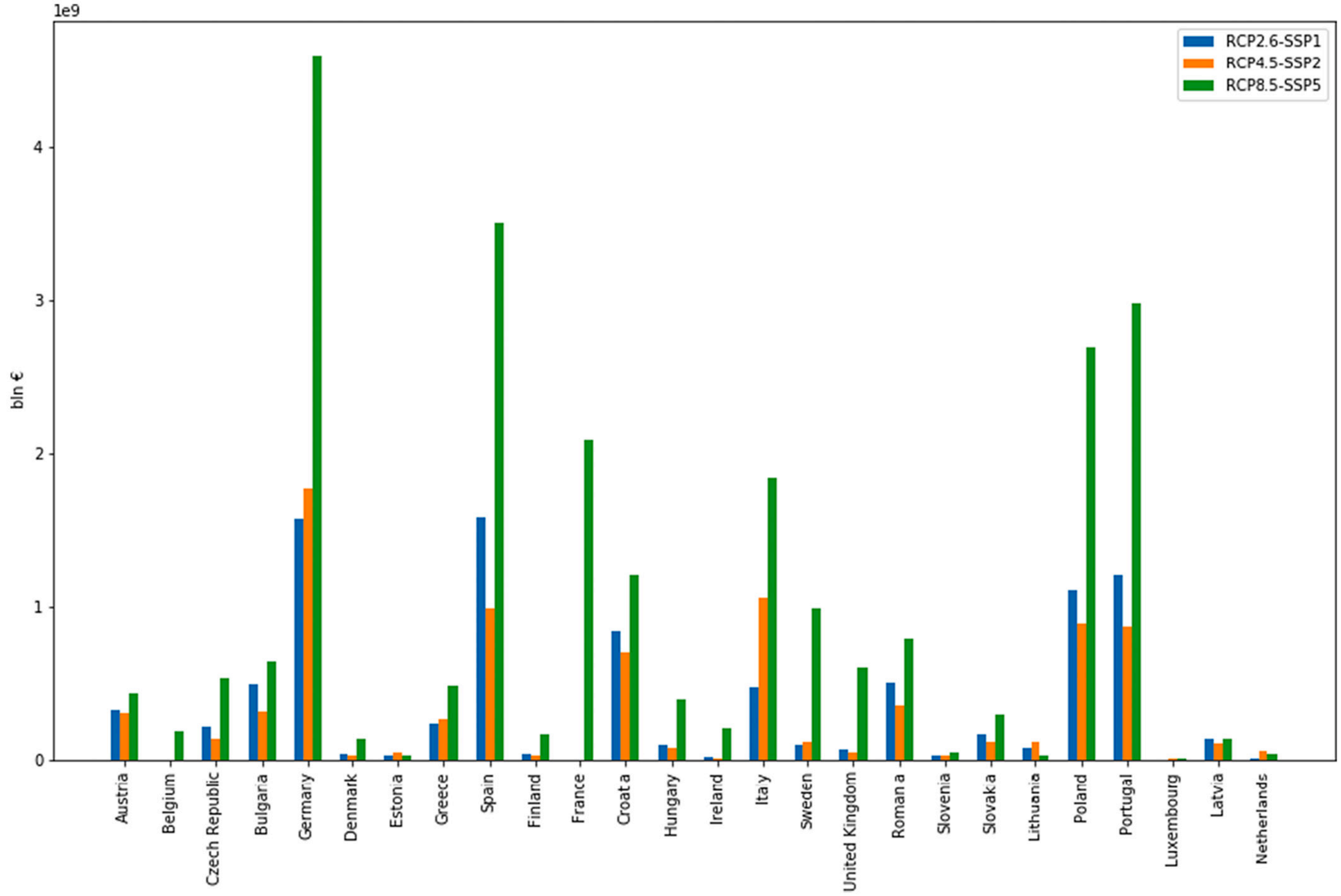


Fig. 7. Uninsured annual flood risk (in bln €/yr) per country under current insurance systems and government compensation arrangements. Results are shown for 3 scenarios of climate and socio-economic change: RCP2.6-SSP1 (blue); RCP4.5-SSP2 (orange); RCP8.5-SSP5 (green). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

to include multiple stylized types of government compensation. For countries that do not maintain flood insurance purchase requirements we identify broadly three types of government responses to uninsured households facing flood damage, which comprise of explicitly abstaining from ex post disaster aid, financing a part of the damage for certain, and providing full compensation of damage while the probability of compensation is assumed to be either known or unknown. EU countries are allocated to one of these stylized forms of government compensation based on literature research. Although the true form of compensation in each country may differ from this generalized system, whether in terms of degree or probability of compensation, the stylized representation of compensation systems allows for an isolated analysis of the derived theoretical predictions of charity hazard. Moreover, with this model setup we are able to compare the impact on insurance demand that varying extents of compensation, as well as different compensation probabilities, have. We are also able to assess how ambiguity regarding compensation affects the household's decision to purchase insurance, by differentiating between a scenario where there is knowledge of the probability of compensation and a situation where this probability is ambiguous. This is an important distinction because in reality the probability of compensation cannot be known, as it is considered to be influenced by factors such as political and economic circumstances.

In addition to including government compensation in the DIFI model, several adjustments were made to the household behavior component of the model to account for the charity hazard effect on flood insurance demand. In particular, to incorporate decision making under uncertainty, ambiguity aversion is implemented in the household decision functions for the countries where this is relevant. This is done using a power function, which inhibits constant relative ambiguity aversion, as is suggested by several studies such as (Krahnen et al., 2013) and (Baillon and Placido, 2019). However, an overview of empirical evidence does not suggest an obvious choice regarding the implementation of ambiguity preferences (Trautmann and van de Kuilen, 2015). For example, in the gain domain, ambiguity aversion is often reported for high-likelihood events, while ambiguity seeking behavior is more evident for low likelihood gains. For this reason, it is important to consider the sensitivity analysis of alternative compositions of ambiguity preferences, which are shown to impact the degree of charity hazard in Figs. C1 and C2. In particular, when individuals are more ambiguity averse this positively impacts insurance demand, presumably because they dislike the ambiguity of government compensation. This is especially evident for regions where flood risk is relatively low, mainly because potential losses are lower there when governments decide not to compensate uninsured damage.

Another noteworthy topic for discussion regarding the application of ambiguity in the DIFI framework is that this is not considered for estimating household responses to the flood risk which we treat as a decision under risk instead of a decision under uncertainty. One reason for this is that households are able to obtain information regarding the probability and impact of flooding, for example, through the flood protection standards that are maintained regionally. Although flood risk estimates are accompanied by uncertainty ranges, they do convey objective information to individuals, which is fundamentally different from government compensation in many countries, where the decision to provide disaster relief, including the amount of compensation, is often taken ad hoc and may be dependent on political interests and financial

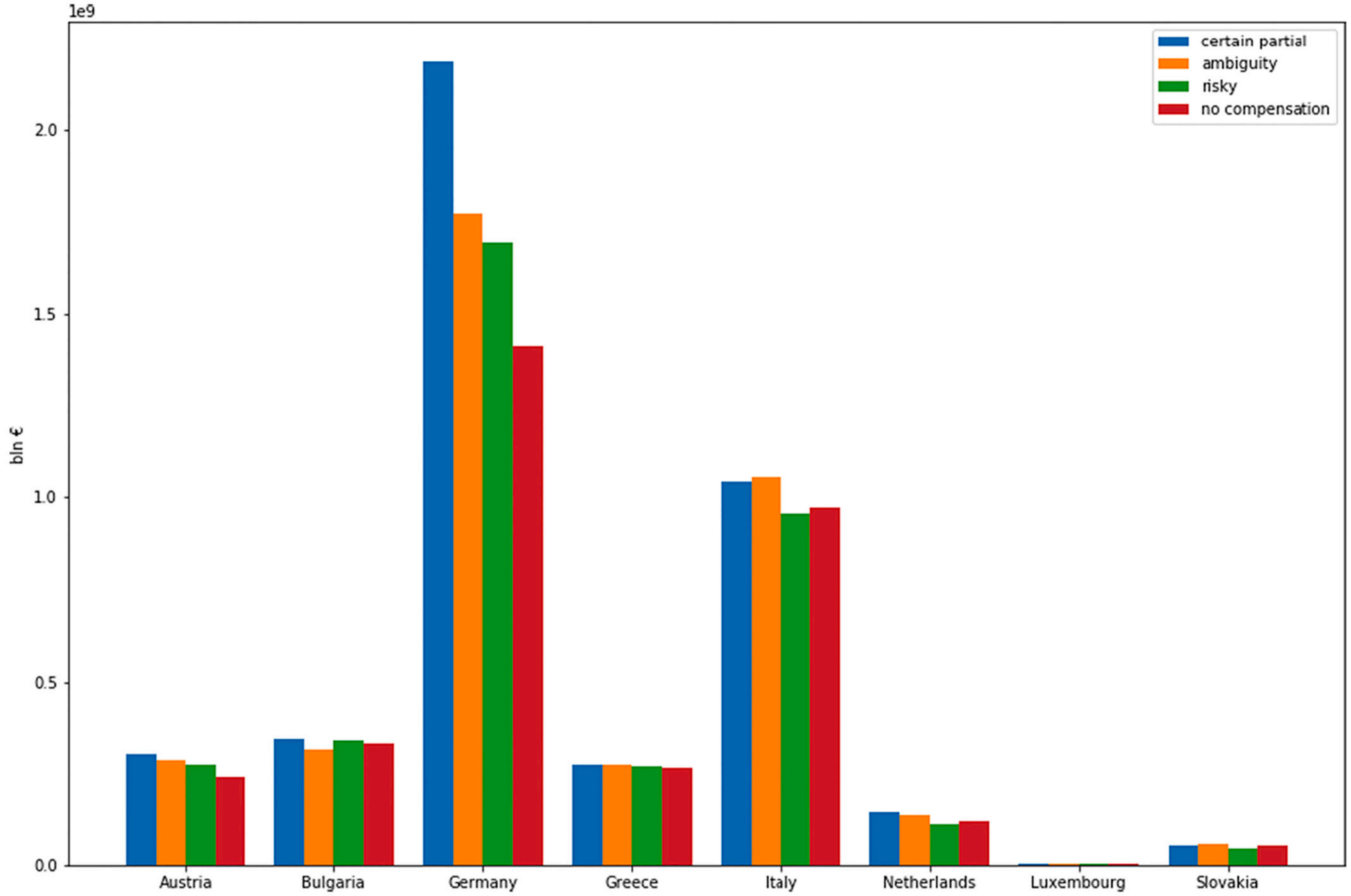


Fig. 8. Uninsured annual flood risk (in bln€/yr) under various forms of government compensation in 2050. Results are shown for countries where government support for uninsured flood damage is currently provided.

circumstances. Therefore, this study differentiates between decision-making under ambiguity of government compensation and decision-making under subjective flood risk. Nevertheless, we recognize that developing a framework to incorporate ambiguity in the modelling of decision-making processes is useful for understanding individuals' behavior in response to natural hazards since the influence of climate change on natural disaster risk is associated with uncertainty. Therefore, we recommend it as a relevant topic for future research.

5.2. Policy recommendations

Some European countries are struggling with a high insurance protection gap as a result of low demand for coverage. Charity hazard is partly responsible for the lack of demand. However, the extent of this effect depends on the anticipated probability and degree of compensation. In this study, we found that ambiguous full compensation of uninsured damage crowds out private flood insurance demand, although to a lesser degree when the probability of compensation is unknown and individuals are ambiguity averse. The highest degree of crowding out occurs when government compensation is certain, even when the extent of compensation is partial. Following these results, ambiguous government compensation is found most compatible with a private flood insurance market. However, uncertainty of compensation after a flood disaster may cause additional problems. For example, government aid to uninsured households affected by hurricane Katrina was slow, unpredictable and poorly managed (Kamel, 2012). This resulted in a delayed reconstruction process, which has been associated with mental health problems in the aftermath of the disaster (Kessler et al., 2008), as well as increasing social segregation (Fussell et al., 2010). For governments, the implicit liability of providing compensation to uninsured households may complicate budgetary planning, as the risk borne by the government is not defined explicitly. When the decision is passed to provide aid, governments may have to resort to borrowing capital, raise taxation, or divert funds from other planned spending. In some countries the impact of flooding can have significant impact on government spending. For example, in Central Europe (Slovakia, Poland, Czech Republic and Hungary) a 1/20 year flood (5% annual probability of occurring) is estimated to cause losses of 2.2–10.7% of total government revenues (Pollner, 2012). As a response to the 2010 Central European Floods, the Czech Republic initiated a special anti-flood tax of approximately €4 monthly for every taxpayer (OECD, 2015).

In Europe the insurance protection gap is identified by (EIOPA, 2019) as a societal challenge that is increasing due to climate- and socio-economic change. How this issue is addressed differs between countries. Besides providing disaster aid, as is thoroughly discussed in this paper, governments can aim to increase protection standards, such as dike heights, in order to lower flood risk, and indirectly the insurance protection gap. A downside of this approach is that increased protection standards may lead to more economic development in these high-risk areas, which causes the potential damage to be larger when a flood does occur (Haer et al., 2020). Furthermore, charity hazard and the insurance protection gap can be limited by stimulating insurance uptake, by for example implementing nudge policies, or introducing insurance purchase requirements. Nudge policies range from passive actions, such as raising flood risk awareness through the provision of information, to more active measures, such as informing households about others in the neighborhood that obtained flood insurance. Flood insurance purchase requirements can be implemented for the whole population, as seen in France and Spain, or part of the population, for example by making insurance uptake a mortgage-requirement, such as in the UK and Hungary. However, implementing insurance purchase requirements may be politically difficult to enact, as has been demonstrated by an attempt in Germany (Schwarze and Wagner, 2007). As refraining from providing financial support to households affected by flooding may be incompatible with welfare states in the EU, the problem of charity hazard is bound to persist and increase reliance on government aid. An alternative to unconditional financial support is to administer low-interest loans to households affected by flooding. According to Kousky et al. (2018) this measure does not crowd out private insurance demand and is, therefore, more compatible with a private flood insurance market.

6. Conclusion

The increasing threat of riverine flooding in Europe due to climate- and socio-economic change calls for an adequate insurance mechanism that can provide financial security to households at risk. A challenge concerning the functioning of private flood insurance markets is the potential crowding out of demand for coverage due to the provision of unconditional disaster aid by the government. As a result of declining uptake of coverage, the ability of insurers to spread risk amongst policyholders decreases. For uninsured households relying on government disaster relief, the provision of public aid can be uncertain, as this is dependent on political and economic circumstances. For this reason, the provision of aid can also be time-consuming, which significantly delays the recovery process after a flood. For governments too, the implicit liability of providing disaster relief can create uncertainty, especially regarding budgetary planning.

Previous studies have verified the existence of charity hazard for flood insurance and explored its extent by means of statistical and theoretical analyses on a local scale. This study uses an EU-scale partial equilibrium model to simulate the extent of charity hazard for various stylized types of government compensation that are designed after practices observed within the EU. After theoretically establishing the crowding out of insurance demand due to government compensation with different levels of uncertainty for its recipients, this study simulates flood insurance uptake using decision functions in an expected utility framework where modelled households anticipate a certain probability and extent of government support after a flood. By applying our simulations of insurance demand over a range of institutional, economic, and future climatic conditions, we are able to project the insurance protection gap. This indicator is the aggregated uninsured flood risk and offers insight into the potential burden of providing flood compensation for public budgets.

In accordance with theoretical predictions presented in this article, the crowding out of insurance demand due to government compensation in our model simulations is most significant when compensation is certain but partial. When compensation of uninsured damage is uncertain, the charity hazard effect is largest when the probability of receiving compensation is objectively known, particularly when individuals are averse to ambiguity. Moreover, higher regional flood risk reduces the degree of charity hazard, which is due to risk averse individuals disliking a spread of potential future wealth states. Considering these general effects of institutional arrangements and flood risk on charity hazard, and taking account of these conditions on a regional scale within the EU and the UK, our simulation exercise finds that charity hazard is an issue that is most prominent in Germany, Slovakia and Italy. The projected insurance protection gap in 2050, assuming insurance systems remain as they are, is highest in Germany, followed by Spain, Portugal and Poland. The large insurance protection gap in these countries is due to relatively high projected flood risk as well as limited insurance uptake. For Germany, the absence of insurance purchase requirements leads to limited demand for coverage, while in Spain, Portugal and Poland, partial uptake requirements or lacking compliance with mandatory uptake leads to only partial coverage of flood risk. Considering these results, insurance uptake and the consequent insurance protection gap can be improved if governments abstain from providing financial aid. However, as this may be a politically infeasible strategy in modern welfare states in the EU, alternative solutions should be considered to raise insurance uptake or provide damage compensation ex post. For example, insurance uptake can be enhanced by nudge policies or enforcing uptake requirements. Alternatively, instead of unconditional government aid, governments can provide low-interest loans to households affected by flooding, which is found to not interfere with demand for flood insurance.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Formal derivations charity hazard

A.1. The model

In the theoretical model, individuals are faced with a choice of whether to insure or not against flood risk. This choice is based on several parameters, such as the impact and probability of flooding, the insurance premium, insurance coverage, and government compensation. The individual is willing-to-purchase insurance if and only if $WTP \geq P(\alpha)$. If $WTP < P(\alpha)$, the individual chooses not to insure.

Consider an individual who has initial wealth, W, and faces a loss, $L \in (0, W)$, with probability p, where $0 < p < 1$. Moreover, insurance coverage, $V = L\alpha$, may be purchased to protect against the potential loss, where $\alpha \in (0, 1)$ is the extent of coverage. The insurance premium is $P = L\alpha p\lambda$, and the loading factor is λ, where $\lambda = 1$ for actuarially fair insurance, $0 \leq \lambda < 1$ for subsidized insurance and $\lambda > 1$ for commercial (positively loaded) insurance. Utility, $U(\bullet)$, is a strictly increasing function defined on final wealth.

If the individual anticipates compensation from the government, θ, where $0 < \theta < 1$, to pay for a proportion of the uninsured losses, his/her expected utility (EU) is as follows:

$$EU = pU[W - P(\alpha) - (1-\theta)(L - V(\alpha))] + (1-p)U[W - P(\alpha)] \tag{A1}$$

Willingness-to-pay for partial insurance ($0 < \alpha < 1$) is denoted WTP. WTP is the premium payment that equalizes expected utility with and without insurance (McIntosh et al., 2019). Expected utility in the case where the individual decides not to insure, EU_{NI}, is defined as:

$$EU_{NI} = pU[W-(1-\theta)L]+(1-p)U[W] = pU[W-WTP-(1-\theta)(L-L\alpha)]+(1-p)U[W-WTP] \tag{A2}$$

In the case of full coverage ($\alpha = 1$), the right hand-side of Eq. A2 becomes $U[W - WTP]$.

A.2. The derivations

The following 4 predictions have been derived theoretically under full insurance ($\alpha = 1$) in Robinson et al. (2021). Here, we consider the special case of partial insurance.

TP1. : Willingness-to-pay for partial insurance is negatively related to the level of government compensation.

From Eq. A2, higher levels of government compensation raise expected utility in the case where the individual decides not to insure, because the share of loss which remains uninsured becomes lower $W - (1 - \theta)L > W - L$. On the right hand-side of Eq. A2, $W - L(1 - \theta)(1 - \alpha)$ also increases in θ, but the increase is smaller than $W - L(1 - \theta)$ because $0 < \alpha < 1$. As a result, WTP on the right hand-side decreases to retain equality of Eq. A2.

$\square$

TP2. : Willingness-to-pay for partial insurance is negatively related to the probability of government compensation for risk averse individuals, holding the expected value of government compensation constant.

Expected utility is as follows, in the case where there is a known probability (π) of government compensation in case of a loss:

$$EU = \pi\{pU[W-P(\alpha)-(1-\theta)(L-V(\alpha))]+(1-p)U[W-P(\alpha)]\}+(1-\pi)\{pU[W-P(\alpha)-(L-V(\alpha))]+(1-p)U[W-P(\alpha)]\} \tag{A3}$$

We assume two government compensation probabilities and amounts, $G_1(\pi_1,\theta_1)$ and $G_2(\pi_2,\theta_2)$. G_1 and G_2 have the same expected value, but differ according to their variances: $\theta_2 > \theta_1$ and $\pi_2 < \pi_1$.The expected utilities in the case where the risk averse (RA) individual decides not to insure across the two scenarios are as follows:

$$\begin{aligned} EU_{NI,1} &= \pi_1\{pU[W-(1-\theta_1)L]+(1-p)U[W]\}+(1-\pi_1)\{pU[W-L]+(1-p)U[W]\} \\ &= \pi_1\{pU[W-WTP_{RA,1}-(1-\theta_1)(L-L\alpha)]+(1-p)U[W-WTP_{RA,1}]\}+(1-\pi_1)\{pU[W-WTP_{RA,1}-(L-L\alpha)]+(1-p)U[W-WTP_{RA,1}]\} \end{aligned} \tag{A4}$$

$$\begin{aligned} EU_{NI,2} &= \pi_2\{pU[W-(1-\theta_2)L]+(1-p)U[W]\}+(1-\pi_2)\{pU[W-L]+(1-p)U[W]\} \\ &= \pi_2\{pU[W-WTP_{RA,2}-(1-\theta_2)(L-L\alpha)]+(1-p)U[W-WTP_{RA,2}]\}+(1-\pi_2)\{pU[W-WTP_{RA,2}-(L-L\alpha)]+(1-p)U[W-WTP_{RA,2}]\} \end{aligned} \tag{A5}$$

Consider the case where $G_1(1,0.5)$ – certain half compensation, and $G_2(0.5,1)$ – risky full compensation:

$$EU_{NI,1} = pU[W-0.5L]+(1-p)U[W] = pU[W-WTP_{RA,1}-0.5(L-L\alpha)]+(1-p)U[W-WTP_{RA,1}] \tag{A6}$$

$$\begin{aligned} EU_{NI,2} &= 0.5\{U[W]\}+0.5\{pU[W-L]+(1-p)U[W]\} \\ &= 0.5\{pU[W-WTP_{RA,2}]+(1-p)U[W-WTP_{RA,2}]\}+0.5\{pU[W-WTP_{RA,2}-(L-L\alpha)]+(1-p)U[W-WTP_{RA,2}]\} \end{aligned} \tag{A7}$$

Eq. A7 can be rewritten as:

$$\begin{aligned} EU_{NI,2} &= 0.5\{U[W]\}+0.5\{pU[W-L]+(1-p)U[W]\} = 0.5pU[W]+0.5(1-p)U[W]+0.5\{pU[W-L]+(1-p)U[W]\} \\ &= 0.5pU[W]+0.5pU[W-L]+(1-p)U[W] = 0.5pU[W-WTP_{RA,2}]+0.5pU[W-WTP_{RA,2}-(1-\alpha)L]+(1-p)U[W-WTP_{RA,2}] \end{aligned}$$

Since $W - L < W - \frac{1}{2}L < W$ and the utility function is strictly increasing in final wealth, we have:

$$U[W-L] < U\left[W-\frac{1}{2}L\right] < U[W]$$

The concavity assumption implies that (similar to Fig. 1 in the manuscript):

$$U\left[W-\frac{1}{2}L\right] > 0.5U[W-L]+0.5U[W]$$

This inequality still holds when both sides are multiplied by p and then added $(1 - p)U[W]$:

$$pU[W-0.5L]+(1-p)U[W] > 0.5pU[W]+0.5pU[W-L]+(1-p)U[W]$$

The left hand-side of the above inequality is $EU_{NI,\,1}$ while the right hand-side is $EU_{NI,\,2}$. This implies that $EU_{NI,\,1} > EU_{NI,\,2}$. Combining this inequality with Eqs. A6 and A7, we have the following:

$$pU[W-WTP_{RA,1}-0.5(L-L\alpha)]+(1-p)U[W-WTP_{RA,1}] > p(0.5U[W-WTP_{RA,2}]+0.5U[W-WTP_{RA,2}-(L-L\alpha)])+(1-p)U[W-WTP_{RA,2}] \tag{A8}$$

The minimum of the left hand-side of Eq. A8 is equal to $U[W - WTP_{RA,\,1} - 0.5(L - L\alpha)]$. The maximum of the right hand-side of Eq. A8 is equal to $U[W - WTP_{RA,\,2}]$. Eq. A8 implies that the minimum of the left hand-side should be larger than the maximum of the right hand-side:

$$U[W-WTP_{RA,1}-0.5(L-L\alpha)] > U[W-WTP_{RA,2}]$$

Since the utility function is strictly increasing, we have:

$$W - WTP_{RA,1} - 0.5(L - L\alpha) > W - WTP_{RA,2}$$

Solving this inequality function, we have:

$$WTP_{RA,1} + 0.5(L - L\alpha) < WTP_{RA,2}$$

$$WTP_{RA,1} < WTP_{RA,2}$$

The willingness to pay under certain half compensation ($\pi = 1$) is lower than the willingness to pay under risky full compensation ($\pi = 0.5$) for risk averse individuals, holding the expected value of government compensation constant.

☐

TP3. : Willingness-to-pay for partial insurance is positively related to the degree of ambiguity aversion when government compensation is ambiguous.

Next we follow the (Klibanoff et al., 2005) smooth ambiguity model, and assume an individual with ambiguity preference, represented by the strictly increasing function, $\varphi(\bullet)$ defined over EU. Note that when ambiguity is present, there is a second-order probability distribution, $F(\overline{\pi})$, where $\overline{\pi}$ is a possible value of π. Under ambiguous government compensation, the Klibanoff et al. smooth ambiguity model value (KMM) is defined according to the second order expected utility function:

$$KMM = E\{\varphi\{\overline{\pi}\{pU[W - P(\alpha) - (1 - \theta)(L - V(\alpha))] + (1 - p)U[W - P(\alpha)]\} + (1 - \overline{\pi})\{pU[W - P(\alpha) - (L - V(\alpha))] + (1 - p)U[W - P(\alpha)]\}\}\} \quad \text{(A9)}$$

$E(\bullet)$ is the expectation with respect to $F(\overline{\pi})$, and we assume two possible objective probability distributions regarding $\overline{\pi}$: either probability 1 is assigned to $\{pU[W - P(\alpha) - (1 - \theta)(L - V(\alpha))] + (1 - p)U[W - P(\alpha)]\}$, or probability 1 is assigned to $\{pU[W - P(\alpha) - (L - V(\alpha))] + (1 - p)U[W - P(\alpha)]\}$.

It is also assumed that an individual is either compensated by the government fully in the case of a loss, or she/he is not compensated by the government. There are subjective probability beliefs represented by $\sigma = (\sigma_1, \sigma_0)$, where σ_1 is the belief that the probability of receiving full government compensation is certain and σ_0 is the belief that the probability of not receiving any government compensation is certain, and $\sigma_1 + \sigma_0 = 1$. Therefore, KMM is defined as:

$$KMM = \sigma_1\varphi\{pU[W - P(\alpha) - (1 - \theta)(L - V(\alpha))] + (1 - p)U[W - P(\alpha)]\} + \sigma_0\varphi\{pU[W - P(\alpha) - (L - V(\alpha))] + (1 - p)U[W - P(\alpha)]\} \quad \text{(A10)}$$

Since we assume $\theta = 1$, the Klibanoff et al. smooth ambiguity model value in the case where the individual decides not to insure, KMM_{NI}:

$$KMM_{NI} = \sigma_1\varphi\{U[W]\} + \sigma_0\varphi\{pU[W - L] + (1 - p)U[W]\} = E\{\varphi\{EU(\overline{\pi})\}\} = \sigma_1\varphi\{U[W - WTP]\} + \sigma_0\varphi\{pU[W - WTP - (L - L\alpha)] + (1 - p)U[W - WTP]\} \quad \text{(A11)}$$

Under linear $\varphi(\bullet)$ (ambiguity neutrality (AN)): $E\{\varphi\{EU(\overline{\pi})\}\} = \varphi\{E(EU(\overline{\pi}))\} \rightarrow$

$$\sigma_1\varphi\{U[W - WTP_{AN}]\} + \sigma_0\varphi\{pU[W - WTP_{AN} - (L - L\alpha)] + (1 - p)U[W - WTP_{AN}]\} = KMM_{NI} = \varphi\{E(EU(\overline{\pi}))\} \quad \text{(A12)}$$

For concave $\varphi(\bullet)$ (ambiguity aversion (AA)): $E\{\varphi\{EU(\overline{\pi})\}\} < \varphi\{E(EU(\overline{\pi}))\} \rightarrow$

$$\begin{aligned}&\sigma_1\varphi\{U[W - WTP_{AA}]\} + \sigma_0\varphi\{pU[W - WTP_{AA} - (L - L\alpha)] + (1 - p)U[W - WTP_{AA}]\} = KMM_{NI} < \varphi\{E(EU(\overline{\pi}))\}\\ &= \sigma_1\varphi\{U[W - WTP_{AN}]\} + \sigma_0\varphi\{pU[W - WTP_{AN} - (L - L\alpha)] + (1 - p)U[W - WTP_{AN}]\}\end{aligned} \quad \text{(A13)}$$

Under convex $\varphi(\bullet)$ (ambiguity seeking (AS)): $E\{\varphi\{EU(\overline{\pi})\}\} > \varphi\{E(EU(\overline{\pi}))\} \rightarrow$

$$\begin{aligned}&\sigma_1\varphi\{U[W - WTP_{AS}]\} + \sigma_0\varphi\{pU[W - WTP_{AS} - (L - L\alpha)] + (1 - p)U[W - WTP_{AS}]\} = KMM_{NI} > \varphi\{E(EU(\overline{\pi}))\}\\ &= \sigma_1\varphi\{U[W - WTP_{AN}]\} + \sigma_0\varphi\{pU[W - WTP_{AN} - (L - L\alpha)] + (1 - p)U[W - WTP_{AN}]\}\end{aligned} \quad \text{(A14)}$$

With both $U(\bullet)$ and $\varphi(\bullet)$ strictly increasing functions, Eqs. A12 to A14 imply that: $WTP_{AS} < WTP_{AN} < WTP_{AA}$.

☐

TP4. : Willingness-to-pay for partial insurance is higher under ambiguous full government compensation vs. risky full government compensation for ambiguity averse individuals.

Using risky full (RF) government compensation G_2(0.5,1), the individual has expected utility in the case where he/she decides not to insure defined in the following way:

$$EU_{NI,RF} = 0.5\{U[W]\} + 0.5\{pU[W - L] + (1 - p)U[W]\} = 0.5pU[W - WTP_{RF}] + 0.5\{pU[W - WTP_{RF} - (L - L\alpha)] + (1 - p)U[W - WTP_{RF}]\} \quad \text{(A15)}$$

For simplicity, we assume $\sigma = (0.5{,}0.5)$ under ambiguous full government compensation (AF). This means that households believe to receive both full and no government compensation with probability 0.5. The Klibanoff et al. smooth ambiguity model value in the case where the individual decides not to insure, $KMM_{NI,\ AF}$:

$$\begin{aligned}KMM_{NI} &= 0.5\varphi\{U[W]\} + 0.5\varphi\{pU[W - L] + (1 - p)U[W]\} = E\{\varphi\{EU(\overline{\pi})\}\}\\ &= 0.5\varphi\{U[W - WTP_{AF}]\} + 0.5\varphi\{pU[W - WTP_{AF} - (L - L\alpha)] + (1 - p)U[W - WTP_{AF}]\}\end{aligned} \quad \text{(A16)}$$

Under linear $\varphi(\bullet)$ (ambiguity neutrality (AN)): $E\{\varphi\{EU(\overline{\pi})\}\} = \varphi\{E(EU(\overline{\pi}))\} \rightarrow$

$$0.5\varphi\{U[W - WTP_{AN}]\} + 0.5\varphi\{pU[W - WTP_{AN} - (L - L\alpha)] + (1 - p)U[W - WTP_{AN}]\} = KMM_{NI} = \varphi\{E(EU(\overline{\pi}))\} = \varphi\{EU_{NI,RF}\} \quad \text{(A17)}$$

Eq. A17 implies that $WTP_{AN} = WTP_{RF}$. The individual is a subjective expected utility maximizer under ambiguity neutrality.

Considering concave $\varphi(\bullet)$ (ambiguity aversion): $E\{\varphi\{EU(\overline{\pi})\}\} < \varphi\{E(EU(\overline{\pi}))\} \rightarrow$

$$\begin{aligned}&0.5\varphi\{U[W - WTP_{AA}]\} + 0.5\varphi\{pU[W - WTP_{AA} - (L - L\alpha)] + (1 - p)U[W - WTP_{AA}]\} = KMM_{NI} < \varphi\{E(EU(\overline{\pi}))\}\\ &= 0.5\varphi\{U[W - WTP_{AN}]\} + 0.5\varphi\{pU[W - WTP_{AN} - (L - L\alpha)] + (1 - p)U[W - WTP_{AN}]\}\end{aligned} \quad \text{(A18)}$$

For convex $\varphi(\bullet)$ (ambiguity seeking): $E\{\varphi\{EU(\overline{\pi})\}\} > \varphi\{E(EU(\overline{\pi}))\} \rightarrow$

$$\begin{aligned} &0.5\varphi\{U[W - WTP_{AS}]\} + 0.5\varphi\{pU[W - WTP_{AS} - (L - L\alpha)] + (1-p)U[W - WTP_{AS}]\} = KMM_{NI} > \varphi\{E(EU(\overline{\pi}))\} \\ &= 0.5\varphi\{U[W - WTP_{AN}]\} + 0.5\varphi\{pU[W - WTP_{AN} - (L - L\alpha)] + (1-p)U[W - WTP_{AN}]\} \end{aligned} \tag{A19}$$

Eqs. A17, A18 and A19 imply that:

$$\begin{aligned} &0.5\varphi\{U[W - WTP_{AA}]\} + 0.5\varphi\{pU[W - WTP_{AA} - (L - L\alpha)] + (1-p)U[W - WTP_{AA}]\} \\ &< 0.5\varphi\{U[W - WTP_{AN}]\} + 0.5\varphi\{pU[W - WTP_{AN} - (L - L\alpha)] + (1-p)U[W - WTP_{AN}]\} \\ &< 0.5\varphi\{U[W - WTP_{AS}]\} + 0.5\varphi\{pU[W - WTP_{AS} - (L - L\alpha)] + (1-p)U[W - WTP_{AS}]\} \end{aligned}$$

Since both $U(\bullet)$ *and* $\varphi(\bullet)$ are strictly increasing functions, the above inequalities imply that:

$WTP_{AA} > WTP_{AN} = WTP_{RF} > WTP_{AS}$.

□

Appendix B. Extended description of simulation approach

B.1. The simulation of flood risk

This section describes in detail how flood risk is estimated using the DIFI model, and provides references for each input data source. Firstly, it is described how flood damage data is estimated in the GLOFRIS model, which combines simulations on flood hazard, exposure and vulnerability. After this, it is explained how flood damage data is applied in the DIFI model to calculate annual flood risk, or expected annual damage (EAD).

Flood hazard is determined as the extent of inundation of land as a result of water-levels that occur with a certain probability, usually expressed as return periods (e.g. expected to occur once every 50 years).[5] Water-levels associated with these return periods are calculated by forcing the GLOFRIS cascade, as presented in (Ward et al., 2013), using time-series data of maximum flood volumes over 1960–1999 from the EU-WATCH project (Weedon et al., 2011). For future projections of flood hazard, the GLOFRIS cascade is run using bias corrected data obtained from “General Circulation Model” (GCM) simulations. These simulations make use of scenarios of future developments in greenhouse gas emissions, known as “Representative Concentration Pathways” (RCPs) (van Vuuren et al., 2011). Similar to the baseline scenario, this is done by taking the average of projections of 40-year periods around the years 2030 and 2050. This process is performed for all CMIP5 GCMs (Taylor et al., 2012).

Exposure to floods is determined by overlaying the obtained flood inundation maps with a land-use map that identifies urban density, which, for the baseline, is obtained from the HYDE database (Klein Goldewijk et al., 2011). The population located in flood risk zones is similarly determined by combining flood inundation maps with population data, which is taken from (Van Huijstee et al., 2018) for current and future developments. We adjust this to the number of households located in flood risk zones by dividing the population by the average number of individuals per household on a country level, which is estimated by (Eurostat, 2020). The value of exposed assets varies per area, which is approximated by accounting for GDP per capita in 2010 (van Vuuren et al., 2007). Future flood exposure is projected based on “Shared Socio-economic Pathways” (SSPs) (Riahi et al., 2017). Developments in built-up areas are provided by (Winsemius et al., 2016), whereas the economic value of exposed assets is determined by adjusting this according to developments in GDP per capita. Finally, vulnerability measures the amount of damage a flood can inflict upon buildings. In GLOFRIS this is simulated using global flood depth-damage functions per occupancy type, which is provided by (Huizinga et al., 2017).

The input data that the GLOFRIS model provides for the current study uses a moderate scenario of climate- and socio-economic change, which is represented by RCP4.5-SSP2. This scenario is broadly aligned with meeting the demands of the “Nationally Determined Contributions” (NDCs) of the Paris Climate Agreement (Hope et al., 2017). In Fig. 7 we test the sensitivity of the results in this study to different scenarios of climate- and socio-economic change. More specifically, in the sensitivity analysis we consider a high-end climate change scenario RCP8.5 in combination with SSP5, which projects high fossil fuel-dependent economic growth. Also, we consider RCP2.6-SSP1, which represents an optimistic future of limited climate change and high economic growth. At this point, as is common practice, we take the average over the CMIP5 GCMs regarding flood risk and exposed population data, which is done to limit biases that may originate from these simulations (Rojas et al., 2012).

The flood risk data, exposed population, and GDP per capita growth are aggregated to the NUTS2-level[6] for further steps in the DIFI model. A first step in this process is to compare inundation levels to local flood protection standards, which are provided by the FLOPROS database (Scussolini et al., 2016). For example, a water level that is expected to occur once every 50 years cannot overtop protection standards that are designed to withstand a 1 in 100 year peak flow. In this study, it is assumed that flood protection standards remain constant, which means that dike heights are raised accordingly to rising flood risk. Nevertheless, climate change may still increase flood risk by increasing inundation depths and extents if dikes fail, due to higher peak river discharges in certain areas. However, in some other areas where climate change is projected to reduce the risk of flooding, this means that existing protection standards are able to withstand more exceptional water levels. The exceedance of flood protection standards is simulated using a damage probability curve, which is fitted based on a power-law function. The DIFI model then uses a Monte Carlo approach to produce estimates of EAD and its variance, which is done by drawing random return period water levels and comparing it to current and future protection standards.

Finally, we adjust the derived flood risk on NUTS2-level to specifically focus on high-risk areas, which we define as areas where floods are expected to occur once every 100 years. This is done by rescaling the EAD on NUTS2-level according to the amount of households located in 1/100 year floodplains. The reason for concentrating the analysis on high-risk areas is that much of the debate about flood insurance uptake, coverage and unaffordability is focused on these areas. For example, in the US, the 1/100 year floodplains are designated as “base flood zones” by FEMA (Federal Emergency Management Agency). Insurance uptake is mandatory for households located in these flood risk-zones that have a mortgage from a federal lending institution (Dixon et al., 2018). In the UK, the flood insurance system is designed to ensure affordability of coverage in high risk areas

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[5] Water-levels are calculated for 9 return periods: 2; 5; 10; 25; 50; 100; 250; 500; 1000 year return periods.

[6] The NUTS regions (nomenclature of territorial units for statistics) is a hierarchical system for dividing up economic territories of the EU, where NUTS2 are basic regions for the application of regional policies (Eurostat).

(Penning-Rowsell et al., 2014), which are demarcated as 1/75 year floodplains (Environmental Agency, 2009).

B.2. The estimation of voluntary flood insurance premiums

Eq. B1 shows how the risk-based premium is determined in the voluntary insurance system, which follows premium setting rules used in various studies (Hudson et al., 2016; Kunreuther et al., 2013; Paudel et al., 2013). The premium $\overline{P}$ is determined per NUTS2-region $\underline{i}$ at time $\underline{t}$, and consists of the premium set by the primary insurer, which is the first segment of Eq. B1, in addition to the reinsurance costs, which is denoted by the superscript RR. The primary insurer covers the policyholder's expected loss $\overline{L}_{i,t}(p)$, as a function of the flood probability $\underline{p}$, subtracted by a deductible $\overline{D}_{i,t}(p)$, which is set at 15% of the loss in accordance with deductible levels reported in (Paudel et al., 2013). Besides the deductible, we assume full insurance coverage associated with the premium $\overline{P}$. The expected loss for the primary insurer is then adjoined by a risk aversion parameter $\underline{r}$, which is taken over the range of losses that are considered insurable $\omega_{0<\varepsilon<99.8}$. The risk aversion parameter can be considered an additional premium that insurers charge for the uncertainty of flood damages. Therefore, this addition to the premium is large if the range of possible losses is large (i.e. if the standard deviation of EAD is large). Following (Paudel et al., 2015), the most extreme and infrequent floods are uninsurable by private insurers, which is why the tail value of flood risk after 99.8% is not covered by insurers. The total risk covered by private insurers is then multiplied by a cost-loading factor $\dot{\lambda}_{c,t}$, which is determined on country-level ($\underline{c}$) and is derived in (Hudson et al., 2019) using OECD insurance statistics of non-life insurance policies. The cost-loading factor represents costs for insurers to provide its services, such as administrative costs. For primary insurers we assume Bertrand competition, which means that no company can charge a profit-loading factor.

The primary insurer transfers the most extreme portion of its risk portfolio to a reinsurer in a stop-loss mechanism, where the reinsurer provides indemnity payments after a certain threshold of claims have been made. This threshold is set at 85%, following optimal stop-loss thresholds derived in Paudel et al. (2015). The calculation of reinsurance premiums is similar to that of primary insurance premiums, except that expected losses and volatility of losses for the reinsurer amount to 15% of total losses, which comprises the total risk transferred by the insurer. An important difference is the reinsurer's loading factor $\ddot{\lambda}_{c,t}$, which in addition to cost-loading contains a profit-loading factor of 50% of the underwritten risk. This high profit margin is enabled by concentrated market power of reinsurers (Froot, 2001).

$$\overline{P}_{i,t} = \left(1+\dot{\lambda}_{c,t}\right)\left(E\left(\overline{L}_{i,t}(p) - \overline{D}_{i,t}(p)\right) + r^{*}\omega_{0<\varepsilon<99.8}\right) + \left(1+\ddot{\lambda}_{c,t}\right)\left(E\left(\overline{L_{i,t}^{RR}}(p) - \overline{D_{i,t}^{RR}}(p)\right) + r^{*}\omega_{0<\varepsilon<99.8}^{RR}\right) \tag{B1}$$

In the modelled voluntary insurance system, households have the opportunity to obtain premium discounts when they implement structural risk-reduction measures to their dwelling. The decision to implement these measures is simulated on household level in the behavior module. The subscript $\underline{j}$ in Eq. B2 denotes that the final premium $P_{i,\ j,\ t}$ is determined on household level, which is calculated by multiplying the remaining risk, after considering the application of risk reduction measures (ER_{DRR}), with the initial premium. For more details concerning this process we refer to (Hudson et al., 2019).

$$P_{i,j,t} = (1 - ER_{DRR})\overline{P}_{j,t} \tag{B2}$$

Appendix C. Sensitivity analysis

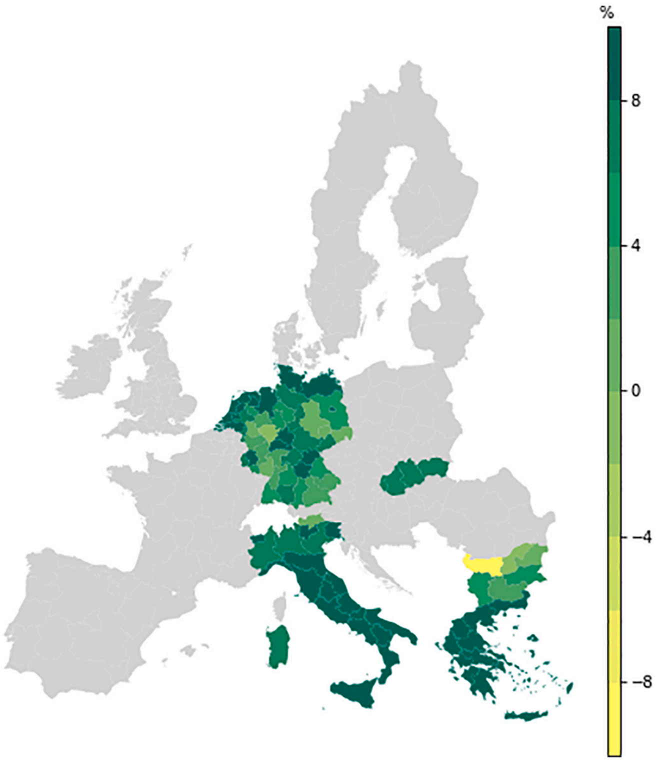

Fig. C1. Sensitivity analysis of ambiguity preference parameter. The difference in insurance uptake when government compensation is ambiguous versus risky in 2020. For this figure an ambiguity preference distribution was used where approximately 40% of individuals were ambiguity averse and 60% ambiguity neutral.

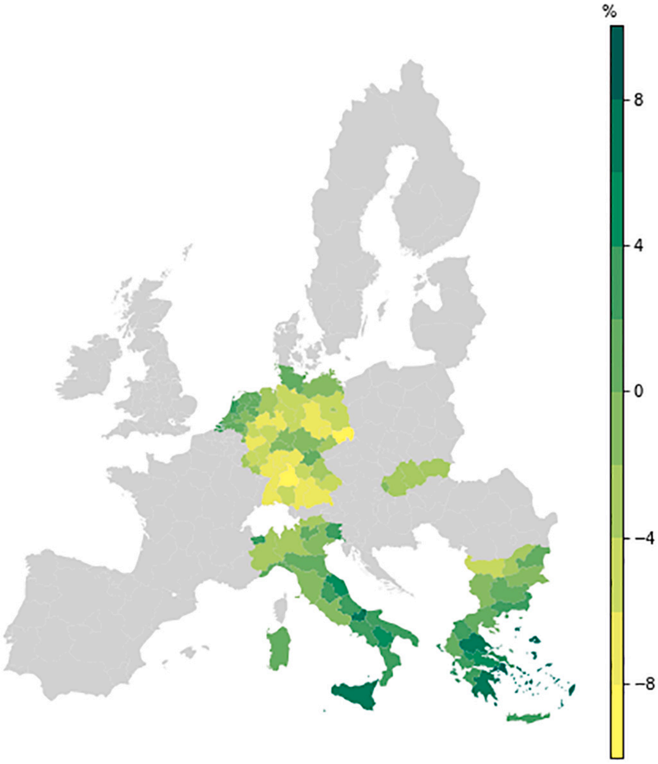

Fig. C2. Sensitivity analysis of ambiguity preference parameter. The difference in insurance uptake when government compensation is ambiguous versus risky in 2020. For this figure an ambiguity preference distribution was used where approximately 12% of individuals were ambiguity averse; 36% ambiguity neutral; and 52% ambiguity seeking.

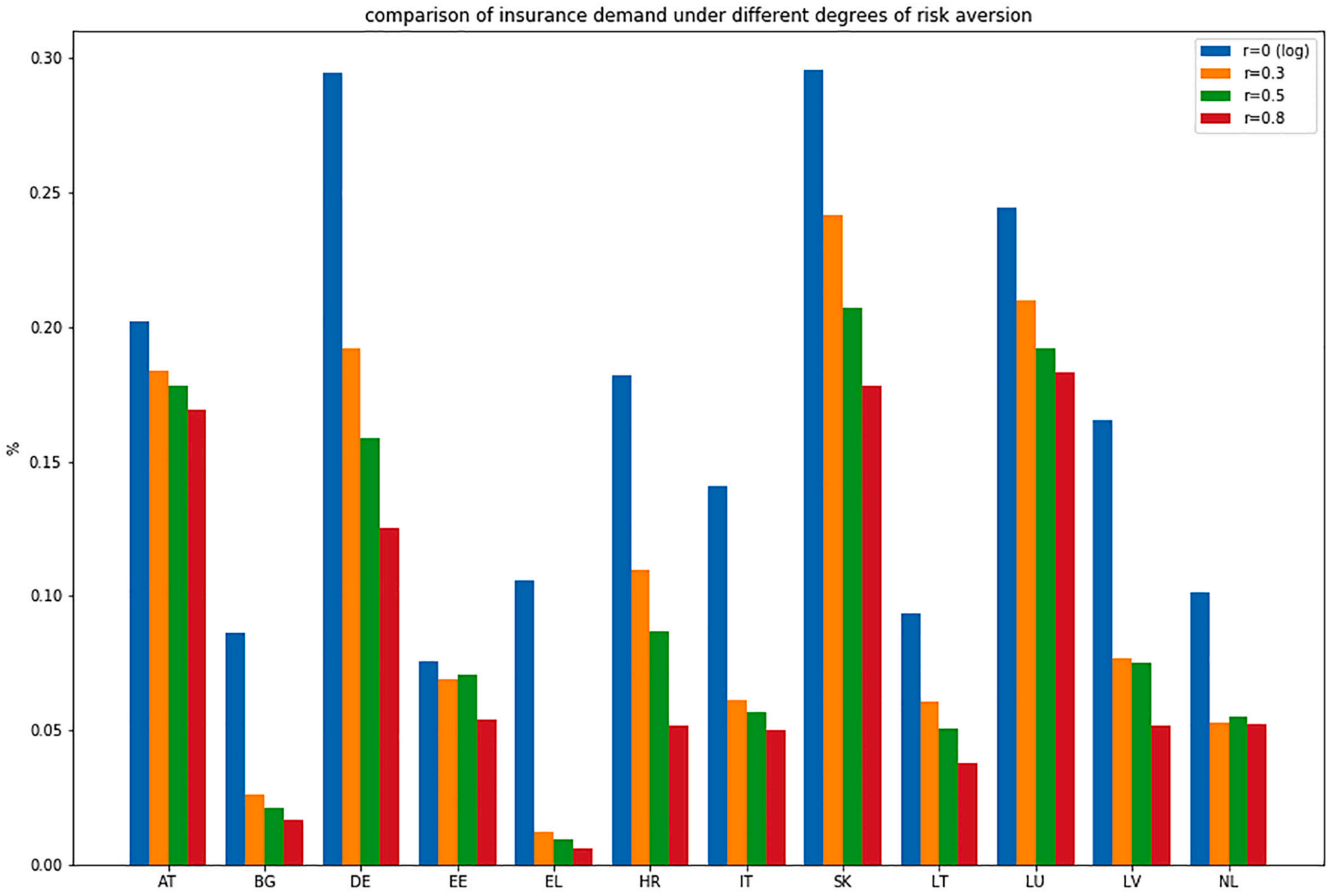

Fig. C3. Insurance penetration rate in 2020 under different degrees of risk aversion r. Under the power utility function risk neutrality arises when $r = 1$, and lower values of r indicate higher degrees of risk aversion. The results are shown for countries where flood insurance uptake is voluntary.

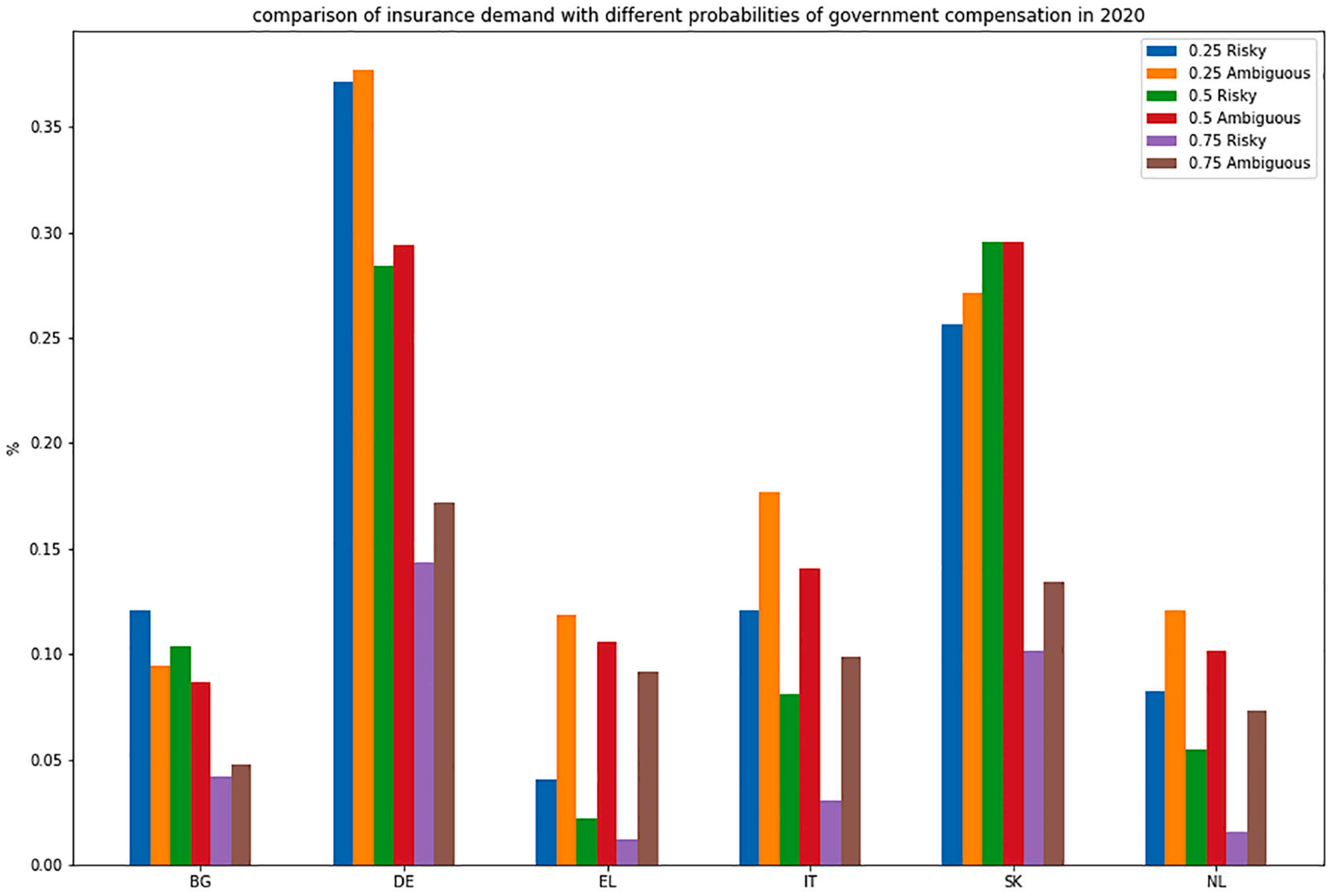

Fig. C4. Insurance penetration rate in 2020 for different probabilities or beliefs about the probability of government compensation. The results are shown both for the "risky" and the "ambiguous" government compensation types. The 0.5 probability or belief is used in the baseline scenario, which is presented in the figures in the manuscript. The remaining columns show the sensitivity of this assumption.

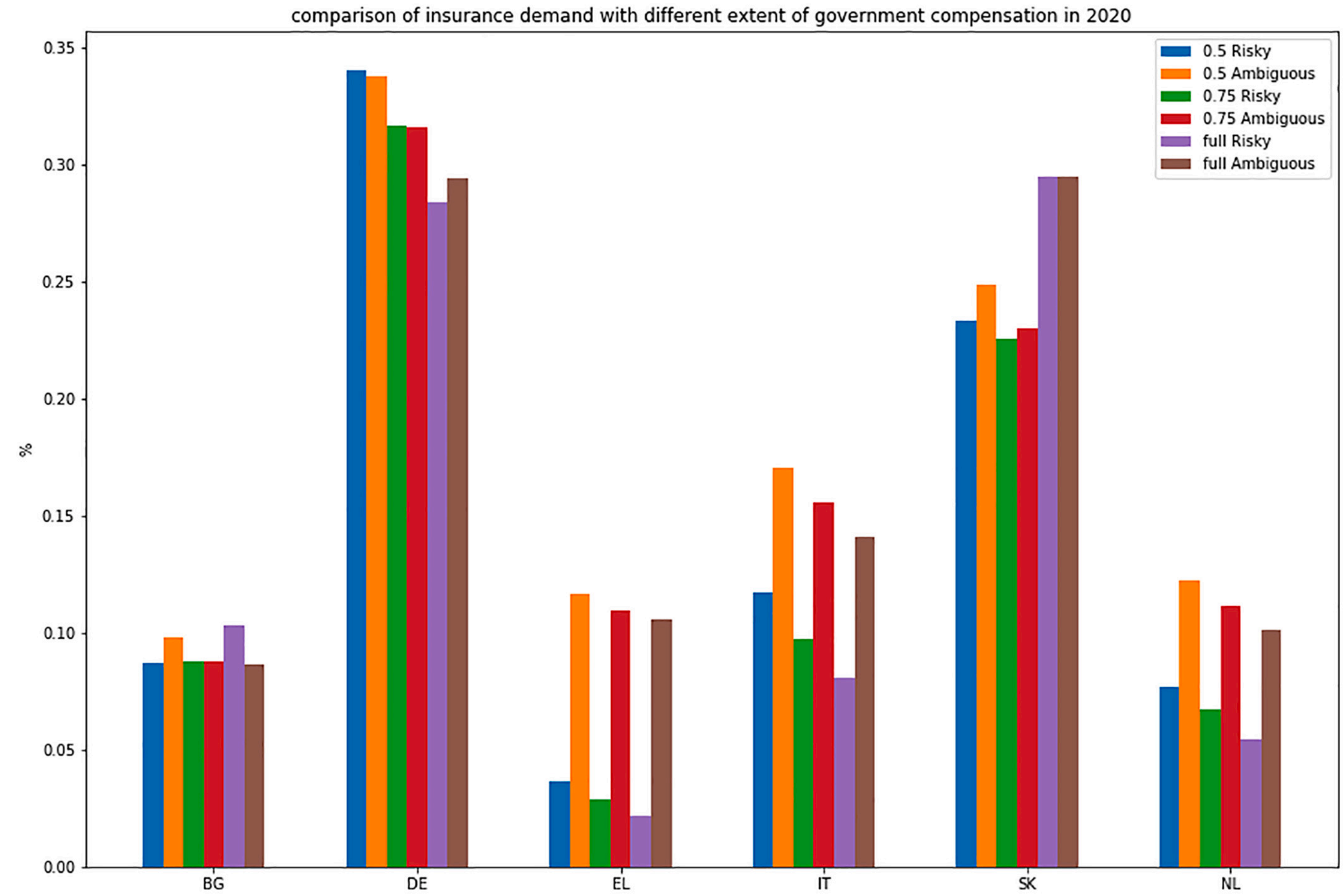

Fig. C5. Insurance penetration rate in 2020 for different amounts of government compensation. The results are shown both for the "risky" and the "ambiguous" government compensation types. The "full" compensation is used in the baseline, which is presented in the figures in the manuscript. The remaining columns show the sensitivity of this assumption.

Appendix D. Allocation of flood insurance and government compensation systems

Country	*Insurance system*	*Compensation type*	*Penetration*	*Sources*
Austria	Voluntary	Certain partial	20–30%	(Le Den et al., 2017); (Hanger et al., 2018)
The public catastrophe fund (Naturkatastrophenfonds) covers a fixed, limited amount of damage (20–30%). Optional additional coverage is available, provided by private insurers. However, privately insured loss is exempt from compensation through the catastrophe fund, which is a major disincentive for purchasing private insurance.				
Bulgaria	Voluntary	Risky/ambiguous	<10%	(Le Den et al., 2017);
Private flood insurance is mostly offered as an extension to general home insurance. The low penetration rate is largely ascribed to ex post government compensation of flood damage.				
Denmark	Semi-voluntary	N/A	>90%	(Le Den et al., 2017; Maccaferri et al., 2012)
Insurance coverage of fresh water lakes and waterways is covered by a mandatory extension to fire hazard policies, which is obligatory for homeowners.				
Germany	Voluntary	Risky/ambiguous	30–40%	(Linnerooth-Bayer et al., 2001; Thieken et al., 2016)
Flood insurance is a voluntary extension of standard home insurance policies, offered by private insurers. Federal and local governments often provide ad hoc compensation to uninsured households, however this occurs less for smaller scale floods. Ex post government support is recognized as a limiting factor for insurance uptake.				
Hungary	Semi-voluntary	N/A	70–75%	(Le Den et al., 2017)
Flood insurance coverage is a mortgage requirement. Insurance companies tend to decline coverage for households with extreme flood risk. For these households a special government compensation scheme is available, which is funded by yearly contributions.				
Italy	Voluntary	Risky/ambiguous	<10%	(Gizzi et al., 2016; Maccaferri et al., 2012)
Flood coverage is a voluntary extension of fire insurance, which is covered by private insurers. The penetration rate is very low, partly as a result of frequent government assistance after floods.				
Poland	Semi-voluntary	N/A	40–60%	(Maccaferri et al., 2012; Matczak et al., 2016)
Flood insurance is a mortgage requirement, otherwise it is optional. Besides private flood insurance coverage, the government guarantees a limited degree of compensation for flood losses for everyone, regardless of whether a household is insured or not.				
Romania	Solidarity	N/A	∼20%	(Hanger et al., 2018; Le Den et al., 2017; Maccaferri et al., 2012)
Flood insurance is compulsory since 2008, with full risk-sharing amongst the population. However, due to low compliance with the mandate, the penetration rate in 2016 is approximately 20%. The low insurance uptake is also due to unaffordability of premiums. There is no possibility for ex post government compensation of flood damage, as was enforced in the same law introduced in 2008.				
Spain	Solidarity	N/A	∼75%	(Le Den et al., 2017)
The Extraordinary Risks Scheme ("*Concorcio de Compensacion de Seguros*" CCS) is a compulsory insurance covering property damages to all natural disasters. Compliance to mandatory insurance is lacking, which makes insurance uptake approximately 75%.				
Sweden	Semi-voluntary	N/A	>95%	(Le Den et al., 2017; Maccaferri et al., 2012)
Insurance coverage for flooding is included in standard homeowner insurance policies, and is also a mortgage requirement, which causes a very high penetration rate.				

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(*continued*)

Country	*Insurance system*	*Compensation type*	*Penetration*	*Sources*
UK	Public-private	N/A	>75%	(Le Den et al., 2017)
Flood coverage is provided by private insurers, which are backed by a reinsurance pool consisting of insurers and the government. Many banks set flood insurance coverage as a mortgage requirement.				
Czech Republic	Semi-voluntary	N/A	~50%	(Maccaferri et al., 2012; OECD, 2016)
A private insurance system with risk-based premiums. Many banks require flood insurance for mortgage applications. However, insurance companies are often unwilling to offer flood coverage in flood-prone areas. Ex-post government compensation has often been made available by the government.				
Portugal	Semi-voluntary	N/A	~50%	(Maccaferri et al., 2012; OECD, 2016)
Flood insurance is part of basic coverage “Fire and Natural Events”, offered by private insurers. Premiums are risk-based, and insurance companies may not offer flood coverage or may charge unaffordable premiums in high-risk areas. Flood insurance is generally required for obtaining a mortgage. The expectation of government compensation and unaffordability seriously limit the penetration rate.				
Greece	Voluntary	Risky/ambiguous	<10%	(“Greece: Insurance and Business, 2021)
Flood coverage is offered by private insurers and is bundled with other types of home insurance. The government allocates disaster aid on an ad hoc basis, as is concluded based on responses to past flood events.				
Finland	Semi-voluntary	N/A	86%	(Rytkönen et al., n.d.)
Flood coverage is included in standard residential property coverage since 2014. The insurance penetration rate of Finnish households is 86% in 2014				
Slovakia	Voluntary	Risky/ambiguous	~30%	(Slavíková et al., 2020; Solín Madajová and Skubinčan, 2018)
Flood insurance for property is offered by private insurers and is optional for households. Uninsured losses are compensated by the government to an estimated degree of 30% based on historical data.				
Slovenia	Semi-voluntary	N/A	~50%	(Maccaferri et al., 2012)
Flood insurance coverage is provided by private insurers and is generally included in most household content policies.				
The Netherlands	voluntary	Risky/ambiguous	<5%	(Botzen and van den Bergh, 2008; Maccaferri et al., 2012)
Riverine flooding has historically been considered uninsurable due to low probability and exceptionally high impact. Recently, one insurer (Neerlandse) started providing insurance coverage for riverine flood risk. Due to the unavailability of flood insurance in the past, the government took responsibility for providing compensation after a flood. However, the amount of compensation is determined by the government ad hoc.				
Estonia	Voluntary	No compensation	Unknown	
Private flood insurance is available, except coverage is limited in one region in Estonia due to regular flooding.				
Latvia	Voluntary	No compensation	~95%	(OECD, 2016)
Flood insurance is an extension of general home insurance policies that is by default included in this insurance package. Homeowners are able to exclude flood risk from the home insurance package if the premium is deemed too high, but the default inclusion of flood risk caused the penetration of flood insurance to be very high (95%). The need for government compensation for uninsured damage is therefore limited.				
Lithuania	Voluntary	No compensation	unknown	
No information found				
Luxembourg	Voluntary	Risky/ambiguous	~5%	(Maccaferri et al., 2012) (Luxembourg Times, 2016; Ries, 2018)
Flood insurance is an optional extension of general home insurance policies. Government disaster relief is often made available after floods, as concluded from news articles. (https://today.rtl.lu/news/luxembourg/a/1191806.html (29-07-2016) https://luxtimes.lu/archives/5671-luxembourg-flood-damage-claims-estimated-between-5-and-10-million-euros (08-06-2018)				
Belgium	Solidarity	N/A	>75%	(OECD, 2016)
Coverage for flood risk is provided by private insurers, although the government guarantees to provide additional coverage if flood damage exceeds a certain threshold. Flood risk is a mandatory extension of natural catastrophe insurance. However, private insurers may refuse to provide coverage in certain high-risk areas. The “*Bureau de tarification – Catastrophes*” has been established to arrange premiums and provide insurance contracts for households for whom insurance is unavailable or unaffordable.				
Ireland	Semi-voluntary	N/A	>90%	(Maccaferri et al., 2012)
Flood insurance is provided by private insurers and uptake is a mortgage requirement. Households that are not, or insufficiently, covered by insurance can obtain government compensation ad hoc through the “Humanitarian Assistance Scheme” (https://www.gov.ie/en/service/12e880-humanitarian-assistance-scheme-swa/).				
France	Solidarity	N/A	100%	(Le Den et al., 2017)
Flood insurance is a mandatory extension to natural catastrophe insurance, which is provided by a private primary insurer, backed by a government reinsurer. Premiums are set by the government and are insensitive to risk. However, deductibles may increase based on the amount of claims made.				
Croatia	Voluntary	No compensation	Unknown	
No information found				

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